1. User's Guide
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CHAPTER 6
BUS TRANSIT CAPACITY

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Factors that influence bus capacity also influence bus speeds and reliability—issues of interest to any size transit agency. See Chapter 3 for a discussion of these relationships.

As discussed in Chapter 3, Operations Concepts, bus capacity is not just an interest of high-ridership, major-city bus systems. The factors that ultimately determine the capacity of a service or facility—dwell time, traffic signal timing, and so on—also affect passenger quality of service elements such as travel speed and travel time reliability, as well as a service provider's operations costs. These are issues of concern to any size transit agency.

Bus capacity, speed, and reliability address the movement of both buses and the movement of people within those buses:

- *Capacity* deals with how many people and buses can move past a given location during a given time period under specified operating conditions; without unreasonable delay, hazard, or restriction; and with reasonable certainty.
- *Speed* deals with how quickly people and buses can move from one location to another.
- *Reliability* deals with how well the bus schedule can be maintained.

Bus capacity, speed, and reliability are influenced by the timing, location, and magnitude of passenger travel demands; by external factors such as traffic signal timing and traffic congestion along the roadways used by buses; and by a transit agency's operating budget and service policies, which influence bus frequencies and allowed passenger loads, among other things. Ultimately, bus capacity is constrained by (a) the ability of bus stops and facilities to serve buses and their passengers, (b) the number and type of buses operated, and (c) the distribution of passenger demand.

Organization of Chapter 6.

Chapter 6 of the *Transit Capacity and Quality of Service Manual* (TCQSM) presents methods for calculating fixed-route bus capacity and speed for a variety of facility types, and provides a summary of the current state of knowledge about factors influencing service reliability.

- Section 2 provides bus-specific speed and capacity concepts, building upon the general concepts information presented in Chapter 3, Operations Concepts. It also presents capacity values suitable for planning analyses.
- Section 3 is an overview of transit preferential treatments (infrastructure improvements) that can improve bus capacity, speed, reliability, or a combination of these.
- Section 4 describes operational tools available to transit agencies that can improve bus capacity, speed, and reliability.
- Section 5 presents a computational procedure for estimating bus capacity.
- Section 6 presents a computational procedure for estimating average bus speeds.
- Section 7 describes current knowledge about the factors that affect bus reliability.
- Section 8 presents potential applications of this chapter's methods to a variety of questions that transit agencies may face.

- Section 9 provides a comprehensive example of the calculations involved in performing bus capacity and speed analyses.
- Appendix A provides substitute exhibits in metric units for selected exhibits that use U.S. customary units.
- Appendix B provides a standardized procedure for collecting bus dwell time data in the field.
- Appendix C discusses the effects of bus bunching on bus capacity.

HOW TO USE THIS CHAPTER

The early sections of this chapter, Sections 2–4, provide bus-specific concepts that support the computational methods presented later in the chapter, but which are also intended to be a useful resource for a wide range of transit and transportation professionals. Section 8, describing applications of this chapter's methods, is written with both non-technical and technical audiences in mind.

Sections 5 and 6 provide step-by-step guidance for performing bus capacity and speed evaluations, and Section 9 gives examples of the calculations involved. Although capacity may not be the ultimate output of an analysis, it is a necessary input to this chapter's speed estimation procedures. Buses interfere with each other as the number of buses using a facility approaches the facility's maximum capacity, thereby reducing average bus speeds. Analysts should be familiar with these sections prior to using the spreadsheet that implements these methods, found on the accompanying CD-ROM. Although Section 7 is less mathematical, as insufficient research exists to present a computational method for estimating bus reliability, this section is also intended primarily for analysts.

Appendix B serves as a resource to those who wish to collect bus dwell time data in the field. Appendix C supplements Sections 5 and 7 with information on bus bunching that, while theoretically sound, has not yet been confirmed through field testing.

OTHER RESOURCES

Other TCQSM material related to bus capacity includes:

- The "What's New" section of Chapter 1, User's Guide, which describes the changes made in this chapter from the 2nd Edition.
- Chapter 2, Mode and Service Concepts, which defines and illustrates the various bus submodes and typical service patterns.
- Chapter 3, Operations Concepts, which defines capacity and presents general capacity, speed, and reliability concepts applicable to all transit modes.
- The "Passenger Load" section of Chapter 5, Quality of Service Methods, which serves as a resource for determining the standing capacity of a bus at a design passenger loading level.
- Chapter 10, Stop and Station Capacity, which provides a method for sizing off-street bus facilities.
- The TCQSM's CD-ROM, which includes a bus speed and capacity spreadsheet and links to electronic versions of all of the TCRP reports referenced in this chapter.

2. FUNDAMENTALS

SOURCES OF BUS DELAY

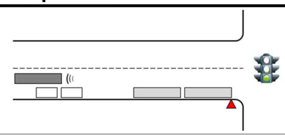
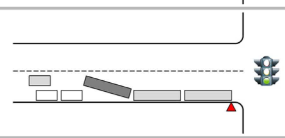
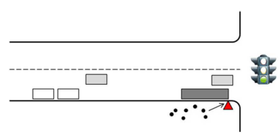
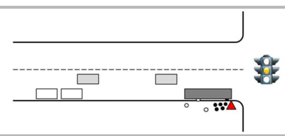
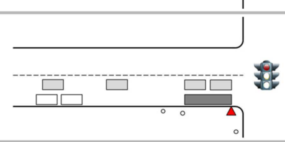
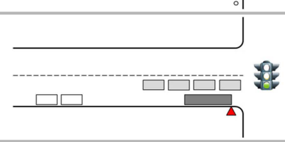
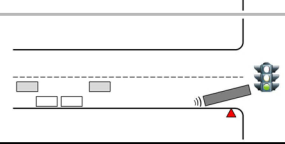
Delay Associated with Bus Stops

Delay affects bus speeds (a quality of service issue) and, ultimately, the cost to operate a bus route.

Without passengers to serve, there would be no point in operating bus service. However, each stop that a bus makes along its route requires time, which affects (a) how fast the route operates, which influences (b) how many buses are required to operate the route, which in turn ultimately sets (c) the cost of operating the route. Therefore, setting bus stop locations requires balancing passenger convenience (which affects ridership) with transit agency operating needs.

Exhibit 6-1 lists the main sources of delay to a bus each time it serves a bus stop, relative to proceeding down the street without stopping. Each of these sources of delay is discussed in more detail following the exhibit.

Exhibit 6-1
Sources of Bus Delay Associated with Bus Stops

Source of Delay	Description	Depiction	Typical Values
Deceleration	Extra time spent slowing to serve a stop, compared to proceeding at the bus' running speed past the stop		4.5 s while slowing from 25 mi/h (40 km/h)
Bus stop failure	Bus arrives at a stop to find all loading areas occupied, forcing the bus to wait until other buses leave the stop		Up to the dwell time and signal delay time of the buses already using the stop
Boarding lost time	Time spent waiting for passengers to walk to the bus door(s) from their waiting position at the stop		Stops with 1 loading area: none Stops with 3 loading areas: 2.5–9 s, depending on loading area position
Passenger service (dwell time)	Time spent opening and closing bus doors, plus time spent for passenger flow onto and off the bus		Minor stop: 10 s Major downtown stop, transit center, park-and-ride: 60 s
Traffic signal delay	Time spent waiting for a green light after passenger flow has been completed		0–70 s, depending on when the bus is ready to depart and the traffic signal cycle length
Reentry delay	Time spent waiting for a gap to pull back into traffic from the bus stop		0–10 s (unsignalized locations), 0 s up to length of green interval (at traffic signals)
Acceleration	Extra time spent speeding up to running speed, compared to proceeding past the stop at the bus's running speed		5.5 s during acceleration to 25 mi/h (40 km/h)

It can be seen from Exhibit 6-1 that dwell time and traffic signal delay are typically the largest contributors to the delay associated with serving a bus stop. However, over the course of a bus route with many stops, even relatively small delays can add up to significant time losses.

Dwell time and traffic signal delay are the largest contributors to bus stop delay.

Deceleration and Acceleration Delay

It takes time for a bus to slow from its running speed to serve a bus stop, and additional time to accelerate back to its running speed after serving the stop. At a comfortable deceleration rate of 4.0 ft/s^2 (1.2 m/s^2) and a typical 40-ft (12-m) diesel bus acceleration rate of 3.3 ft/s^2 (1.0 m/s^2) to 25 mi/h (40 km/h) , a bus takes approximately 10 s longer to travel the same distance, compared to proceeding past the bus stop without stopping. This delay is incurred

At urban street speeds, acceleration and deceleration delay amounts to about 10 s per stop where the bus would not have had to stop anyway due to traffic control.

- Always, at far-side stops at signalized intersections, and at all other bus stops where the bus would not otherwise be required to stop by a traffic control device;
- Sometimes, at near-side stops at signalized intersections and roundabouts, where the bus might have been required to stop anyway due to a traffic control device (traffic signal or YIELD sign); and
- Never, at bus stops located on the near side of a STOP-controlled intersection approach, as the bus would have had to stop anyway for the STOP sign.

The average acceleration characteristics of a bus are dependent on the ultimate speed reached (average acceleration rates are lower when accelerating to higher speeds) and on the bus's propulsion system characteristics. Exhibit 6-2 provides examples of various buses' acceleration characteristics.

Exhibit 6-2 Bus Acceleration Characteristics

	Average Time to Reach Speed (s)			Average Acceleration to Speed (ft/s^2)	
Bus Type	**10 mi/h**	**20 mi/h**	**50 mi/h**	**20 mi/h**	**50 mi/h**
40-ft standard diesel	5.0	8.7	33.2	3.4	2.2
45-ft motor coach diesel	4.0	7.4	27.1	4.0	2.7
60-ft articulated diesel	4.0–4.7	9.1	42.3–43.6	3.2	1.7
Double deck diesel	6.2	10.4	43.6	2.8	1.7
60-ft articulated hybrid	3.8	8.6	35.2	3.4	2.1

Source: *TCRP Synthesis 75* (*1*).

Diesel motor coaches have better acceleration characteristics than other types of diesel-powered transit buses, particularly to high speeds, and this is one reason why these buses are frequently used for commuter bus service that typically operates at freeway speeds. Higher-capacity diesel buses have generally comparable acceleration characteristics to standard diesel buses when accelerating to downtown street speeds, but have worse acceleration when accelerating to higher speeds. However, 60-ft (18-m) articulated hybrid electric buses have acceleration performance that equals or exceeds that of typical 40-ft standard diesel buses.

Acceleration and deceleration delay associated with grade-separated busway speeds is at least 25 s per stop.

Regardless of size or propulsion system, buses have a lower average acceleration rate to freeway or grade-separated busway speeds than to urban street speeds.

A loading area is a curbside position where a single bus can load and unload passengers. Bus stops are formed from one or more loading areas.

Bus stop failure is undesirable from both bus and traffic operations standpoints, but is also unavoidable during near-capacity operating conditions.

Bus Stop Failure

A bus stop served by a large number of buses can experience a condition known as *bus stop failure,* where a bus arrives at a stop only to find that all available loading areas are already being used or are blocked by other buses. In this case, the bus must wait in the street for a loading area to open up, which may not occur until all of the buses already at the stop have finished serving their passengers and (at the near side of a signalized intersection) have a green signal enabling them to proceed down the street.

Bus stop failure is undesirable from a bus operations standpoint, as it negatively affects bus reliability and speed. (Although bus stop throughput is maximized when the next set of buses is already waiting to use the stop, this benefit is more than offset by the speed and reliability impacts.) Bus stop failure is also undesirable from a traffic operations standpoint, as the bus(es) sitting in the street waiting to enter the bus stop block other vehicles using the street. This condition is particularly undesirable at far-side stops, as the buses and other vehicles that are blocked may form a queue that blocks the intersection. Exhibit 6-3 illustrates an extreme case of bus stop failure caused by the a lack of a passing lane at a BRT station.

Exhibit 6-3
Bus Stop Failure Illustrated

Boarding lost time occurs at larger bus stops with multiple loading areas, when there is a delay between the doors opening and the first passenger arriving to board the bus.

Boarding Lost Time

When passengers wait at bus stops with multiple loading areas, such as those found at high-volume BRT stations served by multiple routes, they do not know in advance which loading area their bus will stop at when it arrives. Because a bus will use the frontmost loading area that is available when it arrives, passengers will tend to wait in a location that minimizes their potential walking distance. When a bus arrives, there is a typically a delay, or *boarding lost time,* from the time the bus doors open and when the first passengers arrives to board the bus, depending on where the passengers were waiting relative to where the bus stopped, how quickly they could determine where the bus would stop, and how crowded the platform area was.

Passenger waiting patterns were studied at a busway station in Brisbane, Australia with three loading areas. This study found that passengers tended to concentrate within half a loading area length of the front of the second loading area—the point where the door of the second bus would be located. Once this optimal area became too crowded, passengers first spilled toward the front loading area and, later, toward the rear loading area, but would move into the optimal area when an opportunity presented itself (*2*).

The amount of boarding lost time was found to vary by loading area position and platform crowding level, with median values ranging from 2.4 to 3.5 s and 85th-percentile values ranging from 4.5 to 8.8 s for the stop with three loading areas. Lower platform crowding levels resulted in higher average boarding lost times, as the benefit of faster walking speeds resulting from less crowding was more than offset by a greater percentage of passengers being able to wait in the optimal location, resulting in the first boarding passenger having walked longer on average to a bus arriving at the first or third loading area than under more crowded conditions (*2*).

Each loading area in the Brisbane study was marked with striping for bus drivers and signs for waiting passengers, allowing buses to stop at consistent locations. Electronic next-arrival signs let passengers know when to expect their bus.

Dwell Time

Dwell time is the time a bus spends serving passenger movements, including the time required to open and close the bus doors and boarding lost time. Any extra time the bus spends sitting with the doors open while waiting for a green light after all waiting passengers have been served is part of signal delay time. Door opening and closing time depends on the mechanical properties of a given bus model's doors and whether the bus's kneeling mechanism is used, but typically totals 2 to 5 s (*3, 4*).

The TCQSM defines dwell time as the sum of passenger service time, boarding lost time, and door opening and closing time.

Passenger service time is the largest component of dwell time and is influenced by the following factors:

Many factors influence passenger service time, which is the largest component of dwell time.

- *Passenger demand.* The more people that wish to get on and off the bus, the longer it will take to serve them.
- *Fare payment.* The time required to pay a fare is a major influence on the time required to serve each boarding passenger. Smart card fare payment systems that require passengers to "check out" when leaving the bus will also affect the time to serve alighting passengers.
- *Vehicle configuration.* A bus's floor height relative to the platform level affects service time, as having to ascend or descend steps takes more time than level boarding. If the fare payment system allows passengers to use any door or door channel, then buses with more doors, wider doors, or both, can process passengers faster than buses with fewer or narrower doors.
- *Passenger load.* When standing passengers are present on a bus, it takes more time for boarding passengers to clear the farebox area, making it available for the next passenger to board. Standees can also interfere with the movement of alighting passengers trying to reach a door.
- *Door usage.* Alighting passengers that exit through the front door delay the start of the boarding process. Boarding passengers that block doors used by alighting passengers slow down the alighting process.
- *Platform configuration.* Missing sidewalks or landing pads at bus stops may require the rear bus door(s) to remain closed, concentrating passenger activity at the remaining doors.

Dwell time can vary significantly from one bus to the next serving a stop.

Section 5 provides estimates of the time required for loading wheelchairs and bicycles.

Dwell time can vary significantly from one bus to the next, due to variations in passenger demand between routes serving a given stop, variations in demand from one trip to the next on a given route, and variations in the time required to serve a given number of passengers. Potential sources of the latter type of variation include:

- Passengers with mobility aids, strollers, luggage, etc. that take significantly longer to board and alight than the average passenger;
- Standing loads on some arriving buses that result in longer passenger boarding and alighting times;
- Passengers loading and unloading bicycles from bus-mounted bicycle racks;
- Passenger questions to the bus driver; and
- Fare payment issues (e.g., defective fare media, passengers fishing for change or farecards in their pockets).

Most activities that create extra-long dwell times compared to the average occur randomly and are treated in addition to dwell time.

An operating margin is used to adjust capacity to reflect longer-than-average dwells.

In most cases, these activities occur relatively randomly and are treated in addition to average dwell time. It is nevertheless important to account for them, as unexpectedly long dwell times can result in bus stop failure when the number of buses using a bus stop approaches its capacity. The TCQSM's method for estimating a bus stop's design capacity uses the concept of *operating margin*—extra time allotted in consideration of longer-than-average dwells—to account for these random delays.

Exhibit 6-4 shows average passenger service times associated with level boarding using a variety of fare payment methods. Level boarding is increasingly becoming the standard for bus operations—either through the use of low-floor buses or through raised platforms in the case of some BRT systems—as it provides faster boarding for all passengers, and particularly for passengers with mobility aids. When non-level boarding is required, add 0.5 s/p to the times shown in Exhibit 6-4 for standard stairs (*5*) and 1.0 s/p for the steep stairs typically found on motor coaches.

Exhibit 6-4
Individual Passenger Service Times (Level Boarding)

Situation	Average Passenger Service Time (s/p) Observed Range	Average Passenger Service Time (s/p) Suggested Default
BOARDING		
No fare payment	1.75–2.5	1.75
Visual inspection (paper transfer/flash pass/mobile phone)	1.6–2.6	2.0
Single ticket or token into farebox	2.9–5.1	3.0
Exact change into farebox	3.1–8.4	4.5
Mechanical ticket validator	3.5–4.0	4.0
Magnetic stripe card	3.7–6.5	5.0
Smart card	2.5–3.2	2.75
ALIGHTING		
Front door	1.4–3.6	2.5
Rear door	1.2–2.2	1.75
Rear door with smart card check-out	3.4–4.0	3.5

Sources: Jaiswal (*2*), TCQSM 2nd Edition (*5*), Milkovits (*6*), Diaz and Hinebaugh (*7*), additional research for the TCQSM 2nd and 3rd Editions.

Note: Add 0.5 s/p to boarding times when standees are present. Add 0.5 s/p for non-level boarding (1.0 s/p for motor coaches).

As can be seen from Exhibit 6-4, fare collection activities can sometimes more than double the minimum passenger service time. The placement of the fare collection device(s) and their ease of use has an impact on service times (*6*), as does the complexity of fare payment (e.g., paying with several bills and coins, as opposed to one or two coins) and the susceptibility of fare media to damage (e.g., magnetic-stripe tickets). The information in Exhibit 6-4 can be used to estimate changes in dwell time (and, ultimately, changes in bus travel speeds and route cycle times) associated with changes in fare collection methods and the vehicle–platform interface.

Exhibit 6-4 can be used to evaluate the dwell time and bus speed impacts of changing fare collection methods.

The route cycle time is the time required for a transit vehicle to make one round trip on a route. Along with frequency, it determines how many vehicles are required to operate a route—and the cost.

Traffic Signal Delay

A traffic signal located in the vicinity of a bus stop and its loading areas will serve to meter the number of buses that can enter or exit the stop. For example, at a far-side stop (or a mid-block stop downstream from a traffic signal), buses can only enter the stop during the portion of the hour when the signal is green for the street that the stop is located on. The lower the green time provided to the street, the lower the capacity, and the longer a bus is likely to wait if it has to wait for the traffic signal to turn green again.

Similarly, at a near-side stop, a bus may finish loading passengers but have to wait for the signal to turn green before leaving the stop. As a result, the bus occupies the stop longer than if it would have if it could have left immediately, and capacity is lower as a result. Due to the nature of bus operations, shorter traffic signal cycle lengths offer more opportunities for buses to move through a given signal during the course of an hour. In comparison, at unsignalized locations well away from the influence of upstream traffic signals, buses can enter and exit stops immediately, subject to traffic conditions (accounted for by clearance time, discussed in the next subsection) .

The traffic signal cycle length is the time required to display a complete sequence of traffic signal indications. Shorter cycle lengths are generally better for bus operations, as long as sufficient intersection capacity is maintained.

The effect of traffic signals is accounted for by the *green time ratio* (g/C *ratio*), which is the average amount of effective green time for the traffic movement used by buses, divided by the traffic signal cycle length (the time required to display a complete sequence of traffic signal indications). For example, if traffic moving parallel to a particular bus stop receives a green signal for an average of 54 s, and the total cycle length is 120 s, the g/C ratio at that stop is 54 divided by 120, or 0.45. The g/C ratio at unsignalized locations well away from the influence of traffic signals is 1.00, because bus access to the stop or its loading areas is not metered by a signal.

The combination of traffic signal cycle length and g/C ratio directly affect potential bus delay at a traffic signal. At the traffic signal described above with a 120-s cycle length and a 0.45 g/C ratio, a bus could potentially be delayed up to 66 s if it arrives just as the signal turns red. Shorter cycle lengths reduce the potential delay—for example, the maximum bus delay would be about 34 s with a 75-s cycle and a 0.45 g/C ratio. Longer g/C ratios also reduce potential delay, but to a lesser degree. The purpose of transit signal priority (TSP) treatments (discussed in detail in Section 3) is to minimize these delays, typically by holding the signal green a little bit longer to allow a bus to make it through the intersection, or by returning to green sooner to reduce delay to buses already stopped at an intersection.

Long traffic signal cycle lengths can promote bus bunching, particularly when headways are twice the traffic signal cycle length or less.

Bus operations are not the only consideration in setting traffic signal cycle lengths. Intersection capacity must also be considered, as insufficient capacity creates queues of vehicles that can delay buses trying to approach the intersection. Coordination with other nearby traffic signals is also considered, as is the minimum amount of time needed to serve pedestrian crossing movements. Nevertheless, minimizing the traffic signal cycle length to the extent possible helps reduce bus delay and improve overall bus speeds. In addition, which bus service on a route is frequent (i.e., particularly when headways are twice the traffic signal cycle length or less), long traffic signal cycle lengths can promote the formation of bus bunching, as a bus that misses a green light suddenly ends up a minute or more closer to the bus behind it.

Bus Stop Position

The position of a bus stop relative to the traffic lane affects how easily buses can reenter traffic and continue on their route. The TCQSM defines two bus stop positions: *on-line,* where buses stop in the traffic lane, and *off-line*, where buses pull out of the traffic lane (e.g., into the parking lane or a bus pullout). These are illustrated in Exhibit 6-5.

Exhibit 6-5
On-Line and Off-Line Loading Areas

(a) On-line (Portland)

(b) Off-line (Albuquerque)

With an on-line stop, a bus can resume its route as soon as all passengers have been served and the traffic signal (if present) allows it to proceed. Buses experience no reentry delay with on-line stops. However on-line stops also require vehicles behind the bus to go around the bus (if possible) or to wait until the bus moves to proceed. Some transit agencies (as well as some roadway agencies) require off-line stops when traffic speeds are high (typically above 35 or 40 mi/h [60 or 70 km/h]) for safety reasons. They may also require an off-line stop after several on-line stops on roadways without passing opportunities, to minimize the build-up of vehicles behind the bus and the potential for illegal or unsafe passing maneuvers.

With an off-line stop, and in the absence of yield-to-bus laws, a bus must wait for a gap in traffic before it can reenter the traffic lane and resume its route. At bus stops located at unsignalized locations, this delay typically ranges from 0–10 s, depending on traffic volumes, but can be significantly longer at near-side stops at traffic signals, when the bus has to wait for a long queue of vehicles to clear. As discussed in Section 4, yield-to-bus laws offer the potential to reduce reentry time, depending on motorist compliance with the law. Some transit agencies in jurisdictions without yield-to-bus laws use stickers or signs on the back of the bus to encourage motorists to let the bus back into traffic (*8*). Queue jumps, discussed in Section 3, are another potential tool for addressing reentry delay.

Bus Facility Influences on Delay

In addition to delays associated with individual stops, the roadway facility on which buses operate also contributes delays that affect bus speed, capacity, or both. The most important factors are:

- *Stop spacing*—how often a bus must stop as it travels along a facility;
- *Exposure to general traffic*—the less exclusive the facility, the more buses are exposed to delays caused by other traffic using the facility;
- *Facility design*—in particular, the lack of ability for buses to move around each other or other traffic; and
- *Bus operations*—the number of buses scheduled relative to capacity and how buses and routes are organized.

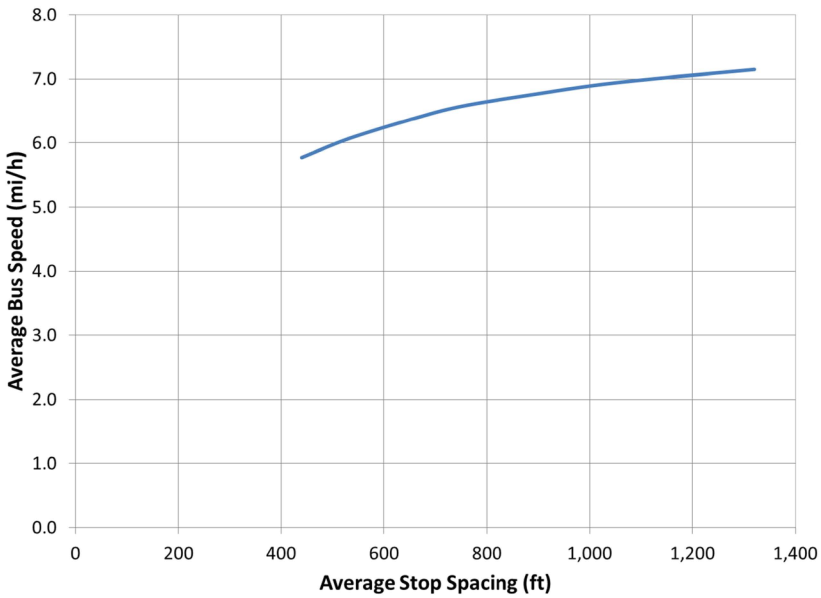
Stop Spacing

As was seen previously, each stop that a bus makes to serve passengers causes the bus to experience some delay. Even in the absence of traffic and traffic signal effects, a bus incurs a minimum of 15 s of delay with each stop on an urban street just to decelerate, open and close the bus doors, and accelerate back to speed. The more a bus stops, the more these delays add up.

Increasing the spacing between stops reduces the overall delay incurred. Even though dwell times will increase at the remaining stops, the overall time saved will result in an improvement in speed. Exhibit 6-6 shows an illustrative case showing the improvement in average bus speed in mixed traffic as stop spacing goes from 12 stops/mi (approximately every 135 m), with a dwell time of 10 s, to 4 stops/mi (every 400 m), with a proportional increase in the number of passengers served per stop.

Increasing stop spacing improves overall bus speeds, even though dwell times increase at the remaining stops.

Exhibit 6-6
Illustrative Relationship of Stop Spacing and Speed (Urban Street, Mixed Traffic)



Notes: Calculated using this chapter's bus speed methodology. Assumes a 15-s dwell time at 12 stops/mi, 3.4 ft^2/s acceleration, 4.0 ft^2/s deceleration, 25 mi/h posted speed, mixed traffic operations within the central business district (CBD), and a proportional increase in passenger service time as stop spacing increases. Assumes scheduled bus volumes are less than half the facility's capacity.

The ability to increase stop spacing depends in part on the quality of the pedestrian network in the area—can pedestrians safely and directly walk to the next-closest stop? It may also depend on the characteristics of the passengers using the stop—for example, persons with limited mobility may find it difficult to walk to the next stop. Finally, local residents may object to losing "their" stop. However, in many cases, the extra time spent walking to another stop will be more than made up with time savings during the trip on the bus, when a stop consolidation program is implemented along an entire route.

Exhibit 6-7 presents average travel speeds for buses operating on grade-separated busways for a variety of average dwell times and stop spacings. Because buses accelerate more slowly to busway speeds than to urban street speeds, each stop produces a minimum of 25 s of delay in addition to the time required to serve passengers. The expected pattern of lower speeds with more frequent and longer stops is also seen here.

Exhibit 6-7
Estimated Average Bus Speeds on Grade-Separated Busways (mi/h)

Average Stop Spacing (mi)	Average Dwell Time (s) 0	15	30	45	60
			50 mi/h RUNNING SPEED		
0.5	31	23	20	17	15
1.0	38	32	28	25	23
1.5	42	36	33	30	28
2.0	43	39	36	34	31
2.5	44	41	38	36	34
			55 mi/h RUNNING SPEED		
0.5	32	24	20	17	15
1.0	41	33	29	26	23
1.5	44	38	34	31	29
2.0	47	41	38	35	33
2.5	48	43	41	38	36
			60 mi/h RUNNING SPEED		
0.5	33	24	20	17	15
1.0	43	34	30	26	24
1.5	47	40	36	33	30
2.0	50	43	40	37	34
2.5	52	46	43	40	37

Source: Calculated using this chapter's methods.
Note: Assumes average 2.2 ft/s^2 acceleration and 4.0 ft/s^2 deceleration rate (40-ft standard diesel bus).
Use the zero dwell time column for express buses slowing, but not stopping at stations (25 mi/h station speed limit and 325-ft-long speed zone through station assumed). Assumes passing lane available for non-stopping buses and no at-grade pedestrian crossings within the station.
A metric version of this exhibit appears in Appendix A.

Exposure to General Traffic

As was discussed in Chapter 2, Mode and Service Concepts, transit facilities can be classified into four main types of operating environments that describe how much protection transit vehicles have from other vehicles:

- *Grade separated*—Only other transit vehicles use the facility and there are no interactions with other vehicles along the facility. Bus facility examples include grade-separated busways and freeway managed lanes that are reserved for buses only.

- *Exclusive*—Only other transit vehicles use the facility, but interactions with other vehicles occur where the facility is crossed by other roadways. Exclusive bus lanes are an example of this type of facility.
- *Semi-exclusive*—Similar to exclusive facilities, but other vehicles are allowed to use the facility under certain circumstances. Bus facility examples include exclusive bus lanes that allow right-turning traffic to use the lanes at intersections and freeway managed lanes that also allow carpools or vehicles that have paid a toll.
- *Mixed traffic*—Buses operate in the same lanes as other traffic and are exposed to a wide range of potential traffic-related delays.

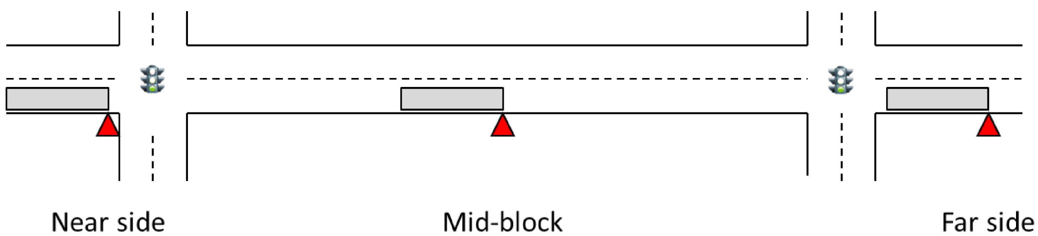
Facility Design

Two other aspects of facility design influence how much other traffic sharing roadway lanes with buses interferes with bus operations: (a) bus stop location and (b) bus ability to pass.

Bus Stop Location

As shown in Exhibit 6-8, on-street bus stops can be located in three places relative to an intersection—near side, far side, and mid-block. Under certain circumstances, such as when buses share a stop with streetcars running in the center of the street, or when a median busway exists, a bus stop may be located on a boarding island within the street rather than curbside.

Exhibit 6-8
On-Street Bus Stop Locations



Far-side stops have the most beneficial effect on bus speeds and capacity, but other factors must also be considered when siting bus stops.

Bus stop location influences bus speeds and capacity, particularly when other vehicles can make right turns from the curb lane (which is typical, except for certain kinds of exclusive bus lanes and at intersections with one-way streets where right turns are prohibited). Far-side stops have the least negative impact on speed and capacity (as long as buses are able to avoid right-turn queues on the approach to the intersection), followed by mid-block stops, and near-side stops.

However, speed and capacity are not the only factors which must be considered when selecting a bus stop location. Potential conflicts with other vehicles operating on the facility, transfer opportunities, passenger walking distances, locations of passenger generators, signal timing, driveway locations, physical obstructions, and the potential for implementing transit preferential measures must also be considered.

For example, near-side stops are often preferable when curb parking is allowed, since buses may use the intersection area—where cars would not be parking in any event—to reenter the moving traffic lane. Near-side stops are desirable where buses make a right turn, while far-side stops are desirable where buses make left turns. At intersections with one-way streets, both traffic and transfer opportunities may need to be considered. If traffic on the one-way street moves from left to right, for example, right-turning traffic volumes might suggest a far-side stop, while providing a convenient transfer to routes on the cross street might suggest a near-side stop.

Mid-block stops are typically only used at major passenger generators or where insufficient space exists at adjacent intersections (*9*). How passengers will cross the street to get to or from a mid-block bus stop must be carefully considered.

Exhibit 6-9 compares the advantages and disadvantages of each kind of bus stop location. Additional guidelines for the spacing, location, and geometric design of bus stops are given in *TCRP Report 19* (*10*). These guidelines must be carefully applied to ensure both good traffic and transit operations.

Exhibit 6-9
On-Street Bus Stop Location Comparison

Location	Advantages	Disadvantages
Far Side	• Minimizes conflicts between right-turning vehicles and buses • Provides additional right-turn capacity by making curb lane available for traffic. • Minimizes sight distance problems on intersection approaches • May encourage pedestrians to cross behind the bus, depending on distance from intersection • Buses can decelerate through the intersection, so less curb space may be needed for the bus stop • Buses can take advantage of gaps in traffic flow created at signalized intersections • Facilitates bus signal priority operation, as buses can pass through intersection before stopping	• Could result in traffic queued into intersection when a bus stops in the travel lane • May obscure sight distance for crossing vehicles • May increase sight distance problems for crossing pedestrians • Can cause a bus to stop far side after stopping for a red light, interfering with both bus operations and all other traffic • May increase the number of rear-end crashes since drivers may not expect buses to stop again after stopping at a red light
Near -Side	• Minimizes interferences when traffic is heavy on the far side of the intersection • Allows passengers to access buses close to crosswalk • Intersection width available for bus to pull away from the curb and accelerate • Eliminates potential for double stopping • Allows passengers to board and alight while bus stopped for red light • Allows driver to look for oncoming traffic, including other buses with potential passengers	• Increases conflicts with right-turning vehicles • May result in stopped buses obscuring curbside traffic control devices and crossing pedestrians • May obscure sight distance for side street vehicles stopped to the right of the bus • Increases sight distance problems for crossing pedestrians • Complicates bus signal priority operation, may reduce effectiveness or require a special queue-jump signal if the stop is located in the parking lane or a right-turn lane • Potentially more difficult to merge back into traffic at traffic signals, due to vehicle queues
Mid-Block	• Minimizes sight distance problems for vehicles and pedestrians • May result in passenger waiting areas experiencing less pedestrian congestion.	• Requires longer no-parking zone • Encourages passengers to cross street mid-block (jaywalking) when no mid-block crossing opportunity provided • Increases walking distance for passengers crossing at intersections if no mid-block crossing opportunity provided

Source: Derived from *TCRP Report 19* (*10*).

Special bus stops are sometimes located along freeway rights-of-way, usually at interchanges or on parallel frontage roads. These stops are used to reduce bus travel times by eliminating delays associated with exiting and reentering freeways. Freeway stops should be located away from the main travel lanes and adequate acceleration and deceleration lanes should be provided. To be successful, attractive and well-designed pedestrian access to the stop is essential (*9*).

Freeway bus stops.

Off-street bus stops, such as transit centers and intermodal terminals, are often designed based on factors other than capacity, including accommodating driver layovers and separating a large number of routes so passengers can easily find their desired buses. Chapter 10, Station Capacity, describes off-street bus stop design.

Off-street bus stop design is discussed in Chapter 10.

Bus Ability to Pass

A bus' ability to pass obstacles in its lane, if a lane is available and traffic permits, is the other facility-related design feature that affects capacity and speed. When a roadway provides two or more lanes in the bus' direction of travel (or, in the case of busways, a passing lane is provided at stations), buses have the potential opportunity to pass other vehicles stopped in their lane, including other buses. This ability decreases as the adjacent lane fills with vehicles, leaving few gaps for buses to use to change lanes.

Bus Operations

Scheduled Volume Relative to Capacity

Once approximately half of a facility's maximum bus capacity is reached, interference between buses using the facility (e.g., an increase in passing activity) causes speeds to drop. The effect becomes more pronounced once approximately 70% of a facility's maximum bus capacity is scheduled. Exhibit 6-10 illustrates the effects of increasing bus lane volumes on bus speeds.

Bus speeds drop once about half of facility's maximum bus capacity is used.

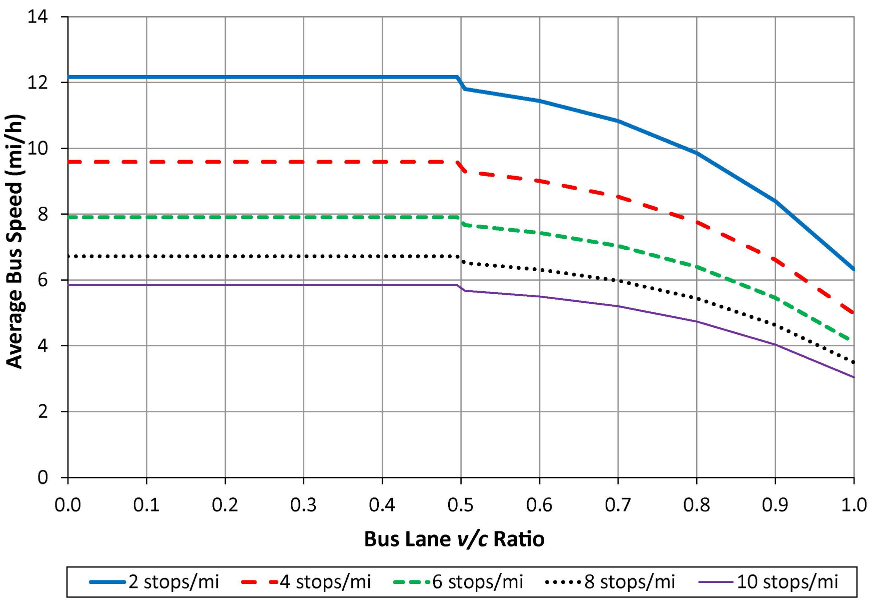


Exhibit 6-10
Illustrative Effect of Bus Volume on Urban Street Bus Speeds

Source: Calculated using this chapter's bus speed methodology.

Notes: Assumes 30-s dwell times, 25 mi/h running speed, CBD bus lane with right-turn delays, and typical signal timing. *v/c* ratio = volume-to-capacity ratio.

Bus Stopping Patterns

How buses are organized when using a facility also affects speed and capacity. *Platooning,* where two or more buses travel the facility as a group, results in bus stops being used more efficiently. *Skip-stop operation,* where bus routes are divided into two or more groups that use separate sets of stops along the facility, allows many more buses to share a facility than if all buses used the same set of stops. Both of these techniques are described in more detail in Section 4 of this chapter.

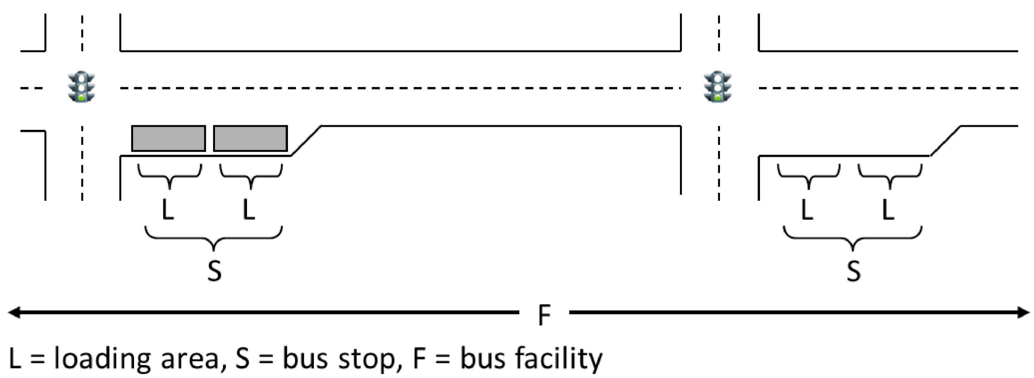
FACTORS DETERMINING BUS CAPACITY

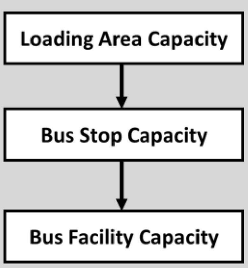
Capacity Calculation Process

Bus capacity is calculated for three key locations, illustrated in Exhibit 6-11:

1. *Bus loading areas (berths),* curbside spaces where a single bus can stop to load and unload passengers;
2. *Bus stops,* consisting of one or more adjacent loading areas; and
3. *Bus facilities,* continuous sections of roadways used by buses that include at least one stop, but typically many more.

Exhibit 6-11
Bus Loading Areas, Stops, and Facilities





The capacity of a single loading area is a key input into determining the capacity of a bus stop. Likewise, the capacity of the critical bus stop is a key determinant of the bus facility capacity.

As is the case throughout the TCQSM, capacity can be determined for both vehicles (in this case, buses) and persons, and it can be determined both as a *maximum capacity,* maximizing throughput without regard for reliability or operational issues, and as a *design capacity,* the number of buses or persons that can be served at a desired quality of service. When not specified otherwise, “capacity” means design capacity.

Loading Area Capacity

The capacity of a loading area can be simply expressed as follows:

Equation 6-1

$$\text{Loading area capacity} = \frac{\text{Seconds in an hour available for bus movement}}{\text{Seconds that a design bus occupies the loading area}}$$

The number of seconds in an hour available for bus movement is 3,600 s/h, multiplied by the percentage of the hour that buses can access the loading area—100% for stops away from traffic signals, or the g/C ratio for stops at traffic signals.

The seconds that a design bus occupies the loading area consists of the following:

- Average time spent serving passengers while the traffic signal is green (the average dwell time multiplied by the g/C ratio);
- Possible reentry delay waiting for a gap in traffic to exit the stop;
- Average time for a bus to travel its own length, freeing up the curb space for another bus to pull in behind it (dead time not usable by buses); and
- An operating margin that reduces maximum capacity to design capacity, by adding in the number of seconds that a design bus with a longer-than-average dwell time would occupy the stop at the design failure rate.

All of these factors were addressed previously in the subsection on bus delay.

Bus Stop Capacity

The capacity of a bus stop consists of the capacity of a single loading area at the stop, multiplied by the equivalent effectiveness of all the loading areas forming the stop, and by the percentage of time that movement into and out of the stop is allowed by traffic control devices, such as traffic signals.

Loading Area Effectiveness

The more loading areas available at a bus stop, the greater the bus stop's capacity, because more buses can load and unload passengers simultaneously. However, some designs are more efficient than others at adding capacity, depending on whether they allow independent bus movement into and out of the loading area.

There are four typical loading area designs, as shown in Exhibit 6-12: linear, sawtooth, drive-through, and angle. Linear loading areas are typically used for on-street bus stops, as they require the least amount of space. However, they typically operate on a first-in, first-out basis, which can result in one bus blocking other bus' ability to access loading areas or to leave immediately once their passengers have been served. The other three loading area designs are termed *non-linear loading areas,* and their designs allow buses to pull in and out of loading areas independently of each other.

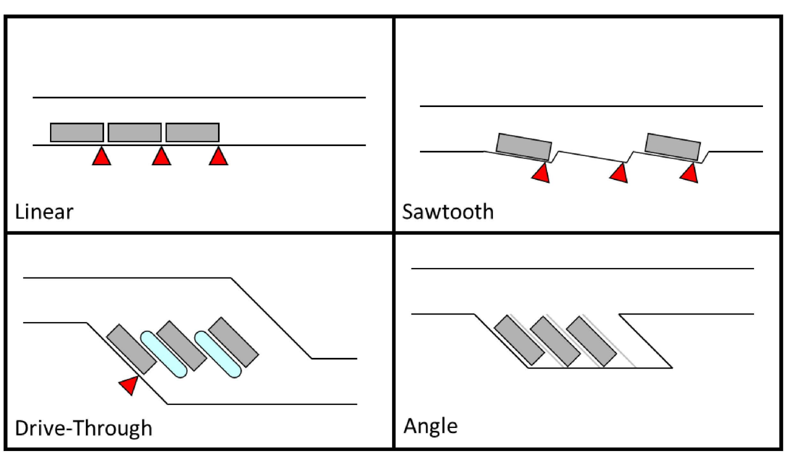


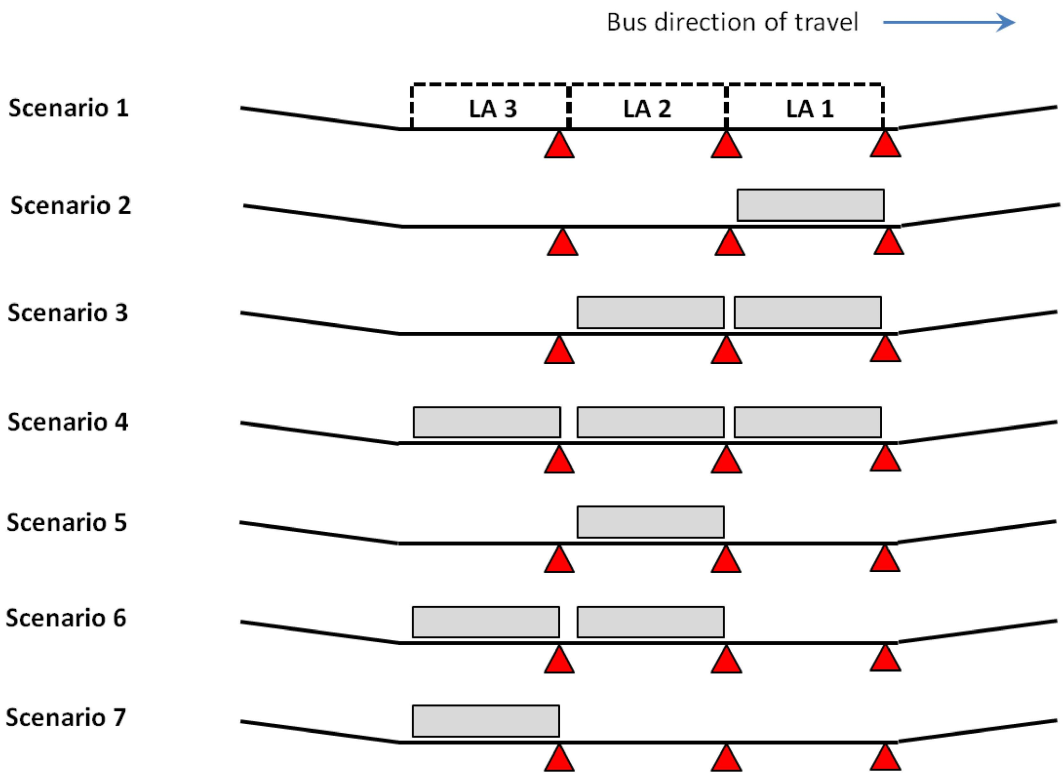
Exhibit 6-12
Loading Area Design Types

Non-linear loading area designs are fully effective: doubling the number of loading areas doubles the stop's capacity.

Non-linear designs are *fully effective*: doubling the number of loading areas doubles the stop's total bus capacity. The full effectiveness results from buses being able to move independently of each other. In addition, buses are typically assigned to a particular loading area when non-linear designs are used, so no boarding lost time occurs when several buses arrive at once. Because of the extra space required, non-linear designs are rarely seen at on-street locations, except at on-street transit centers.

Exhibit 6-13 shows the possible ways that a bus stop consisting of three linear loading areas can be utilized. The loading areas are numbered from1 to 3, with loading area 1 being the front-most loading area.

Exhibit 6-13
Loading Area Utilization Example



Source: Based on Jaiswal (*2*).
Note: LA = loading area.

Doubling the number of linear loading areas at a stop increases capacity by less than a factor of 2, due to bus blocking effects.

In Scenario 1, the bus stop is empty. The first bus to arrive will stop at loading area 1, as in Scenario 2. If a second bus arrives before the first bus departs, it will stop at loading area 2, as shown in Scenario 3. A bus in loading area 2 is blocked from leaving the stop until the bus in loading area 1 leaves. (When scheduled bus volumes are well under the stop capacity, a bus in loading area 2 could leave more room between itself and the bus in loading area 1, allowing it to exit independently. However, it would block access to loading area 3 in the process.)

In Scenario 4, all three loading areas are utilized, but bus #2 is blocked from leaving by bus #1, and bus #3 is blocked by both buses in front of it. If bus #1 is the last to finish serving passengers, all three buses will exit the stop as a platoon.

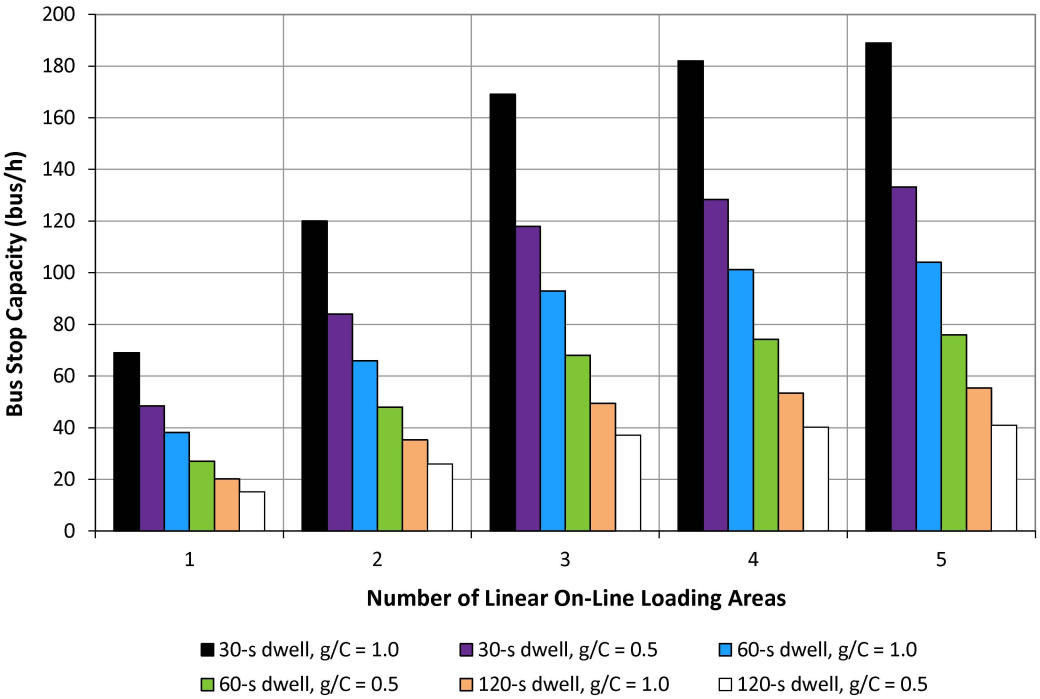
In Scenario 5, a bus in loading area 1 departed after the bus in loading area 2 arrived. If another bus arrives before bus #2 is ready to leave, it will have to stop in loading area 3, as bus #2 blocks access to loading area 1, leaving its potential capacity unavailable for the moment (Scenario 6). If yet another bus arrives, bus stop failure will occur, because loading area 3 is occupied and the arriving bus is blocked from using loading area 1 by the other two buses.

Finally, in Scenario 7, a bus occupies loading area 3. The next bus to arrive will experience bus stop failure, as its access to loading areas 1 and 2 is blocked. Two-thirds of the stop's potential capacity is unavailable for the moment.

As this example illustrates, as more loading areas are added to a bus stop, the greater the likelihood that one or more loading areas will be blocked or will block other loading areas. Therefore, the extra capacity provided by another loading area drops with each additional loading area added to the stop. The TCQSM uses the concept of *effective loading areas* to describe the fractional capacity added by another loading area.

Exhibit 6-14 illustrates the diminishing effect of adding additional linear loading areas to a bus stop. It shows maximum on-line bus stop capacity for selected dwell times and g/C ratios, based on a 10-s clearance time and random bus arrivals at the stop. *Increasing the number of linear loading areas has a much smaller effect on changes in capacity than reducing dwell times.* Note that for dwell times greater than 60 s, the differences between a g/C of 0.5 and 1.0 are small.

Exhibit 6-14
Relative Contributions of Dwell Time, *g/C* Ratio, and Number of Loading Areas to Bus Stop Maximum Capacity



Note: Calculated using this chapter's bus capacity methodology. Based on 10-s clearance time, 25% failure rate, 0.6 coefficient of variation of dwell times, and random bus arrivals at on-line stops.

Traffic Congestion Effects

When right turns are allowed from the curb lane, queues of cars waiting to turn right may block bus access to a near-side stop. Queues of cars may also block bus access to a far-side stop, but if another lane is available and traffic permits, buses may be able to change lanes to move around the queue. To the extent that buses are blocked, however, some of the traffic signal green time that would otherwise be available for bus movement into the bus stop is made unavailable, reducing the overall stop capacity.

Bus Facility Capacity

The capacity of a bus facility is determined by the capacity of the critical stop along the facility. The critical stop will be the bus stop used by all buses that has the lowest capacity. There are two exceptions to this general rule:

A managed lane is a lane that restricts usage to certain vehicle types—for example, buses and carpools or buses and toll-paying vehicles.

1. Grade-separated facilities without stops (e.g., freeway managed lanes) or with passing lanes at stops (e.g., grade-separated busways) act as pipes; their capacity will typically be constrained at a point before or after the facility (for example, by the capacity of the bus terminal that the facility feeds).
2. Skip-stop operation separates bus routes into groups that stop at different sets of stops along a facility. In this case, the sum of the critical bus stop capacity of each group becomes the starting point for determining bus facility capacity, allowing a nearly two- to four-fold increase capacity, depending on the number of stop patterns used.

Person Capacity

Person capacity can be determined as either a *scheduled* person capacity or a *design* person capacity. The former determines how many people *can* be reliably served in an hour under the current schedule; the latter determines how many people *could* be served if the facility was operated at capacity, given a set of design criteria or assumptions (e.g., vehicle mix, design failure rate).

Person capacity is based on the number of vehicles that are or could be operated on the facility and the design passenger capacity of those vehicles. The design passenger capacity is set based on (*a*) quality of service considerations and (*b*) a desire to avoid pass-ups (i.e., allowing some unused space to accommodate surges in demand from one trip or day to the next).

Typical bus vehicle types, dimensions, and passenger capacities are given in Exhibit 6-15. Note that in any transit vehicle, the total passenger capacity can be increased by removing seats and making more standing room available. This lowers the quality of service provided to passengers, when passengers must stand who would not have done so otherwise, but also frees up space that can be put to specialized use (e.g., stroller storage) (*1*).

Exhibit 6-15
Characteristics of Common Bus Transit Vehicles—United States and Canada

Bus Type	Length (ft)	Floor Level	BRT Features	Passenger Doors	Seats	Maximum Standees [a]
Small bus/minibus	18–30	High	None	1	8–30	NA
Standard bus	35	High	None	2	35–40	NA
	35	Low	None	2	30–35	NA
	40	High	None	2	40–45	NA
	40	Low	None	2	37–43	30–34
	40	Low	Styling	2	39–47	32–46
	40	Low	Styling	3	33	49
Double-deck	40	Low	None	2	79–89	10–15
Motor coach	45	High	None	1	53–65	0[b]
Articulated	60	High	None	2–3	65	NA
	60	Low	None	2–3	61–64	53–57
	60	Low	None	3–4	43	57
	60	Low	Styling	2–3	58	NA
	60	Low	Styling	3–5	64	53
	65	Low	Styling	2–3	67	NA
Purpose-built BRT	60	Low	Yes	3/6[c]	37	67
	60	Low	Yes	4	27	90

Sources: *TCRP Synthesis 75* (*1*), TCQSM 2nd Edition (*5*), *TCRP Report 118* (*11*).

Notes: NA = not available from manufacturer.

(a) Crush load conditions. Depending on available standing area and transit agency policy, design bus standee load is typically 25–50% of the seated capacity, unless seats have been removed to add standing room or other uses (e.g., interior luggage or bicycle racks).

(b) Typically used in high-speed environments where it is desirable to have all passengers seated.

(c) Option for three doors on both sides.

PLANNING-LEVEL CAPACITY VALUES

The bus capacity analysis methodology presented in Section 5 provides a highly detailed treatment of bus operations. The level of precision inherent in that analysis may exceed the accuracy of the available data. In contrast, for planning purposes, the only requirement is a concept for a potential improvement and a general understanding of how existing service operates.

Bus Volume and Capacity Relationships

The observed peak-hour bus movements along freeways and city streets, and to or from bus terminals, provide guidelines for estimating the capacity of similar facilities. They also provide a means of checking or verifying more detailed capacity calculations. General planning guidelines are presented in Exhibit 6-16 that match scheduled bus volumes on downtown streets and arterial streets leading to the city center to qualitative descriptions of bus flow along those streets. Where stops are not heavily patronized (e.g., outlying urban streets), bus volumes could be increased by about 25%.

Exhibit 6-16
Planning-Level Bus Lane Service Volumes

These service volumes may be used for planning purposes. More precise values for operations and design purposes should be computed from the capacity relationships and procedures presented later in the chapter.

Description	Service Volume bus/lane/h	Average bus/lane/h
ARTERIAL STREETS		
Free flow	25 or less	15
Stable flow, unconstrained	26 to 45	35
Stable flow, interference	46 to 75	60
Stable flow, some platooning	76 to 105	90
Unstable flow, queuing	106 to 135	120
Forced flow, poor operation	over 135*	150*
DOWNTOWN STREETS		
Free flow	20 or less	15
Stable flow, unconstrained	21 to 40	30
Stable flow, interference	41 to 60	50
Stable flow, some platooning	61 to 80	70
Unstable flow, queuing	81 to 100	90
Forced flow, poor operation	over 100*	110*

Sources: Hoey and Levinson (*12*) and *Transportation Research Circular 212* (*13*).

Notes: *Results in more than one-lane operation. The values for forced flow conditions should not be used for planning or design. They are merely given for comparative purposes.

Bus volumes shown assume all buses make regular stops along the street.

The number of people per hour that can be served by standard buses on exclusive bus lanes at various bus flow rates and passenger load factors are given in Exhibit 6-17. This exhibit provides a generalized planning guide that assumes that key boarding points are sufficiently dispersed to achieve these bus loads. It suggests *maximum* person-flow rates of about 6,450 people per hour per lane on downtown streets and 8,700 people per hour per lane on arterial streets. Corresponding maximum values for *seated* passenger flows are 4,300 and 5,800 people, respectively. Exclusive use of articulated or double-deck buses would increase these values by one-third to one-half.

Exhibit 6-17
Maximum Standard Bus Passenger Service Volumes for Planning Purposes

	Load Factor (p/seat)				
Buses per Hour	**0.00-0.50**	**0.51-0.75**	**0.76-1.00**	**1.01-1.25**	**1.26-1.50**
ARTERIAL STREETS					
25 or less	535	805	1,075	1,340	1,610
26 to 45	965	1,450	1,935	2,415	2,900
46 to 75	1,610	2,415	3,225	4,030	4,835
76 to 105	2,255	3,385	4,515	5,640	6,770
106 to 135	2,900	4,350	5,805	7,255	8,705
DOWNTOWN STREETS					
20 or less	430	645	860	1,075	1,290
21 to 40	860	1,290	1,720	2,150	2,580
41 to 60	1,290	1,935	2,580	3,225	3,870
61 to 80	1,720	2,580	3,440	4,300	5,160
81 to 100	2,150	3,225	4,300	5,375	6,450

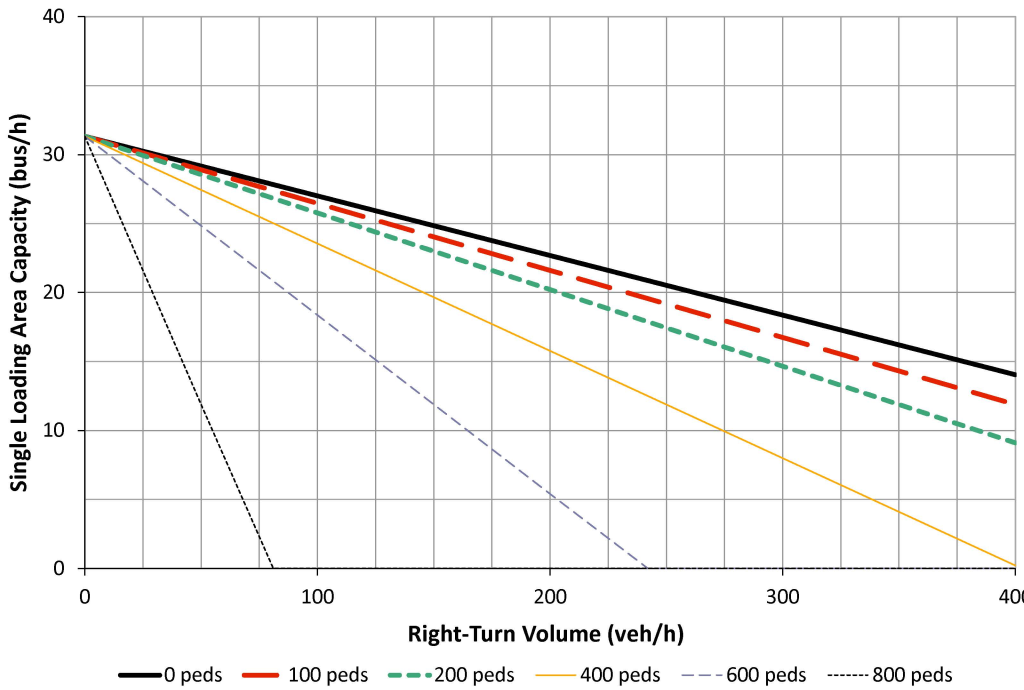
Note: Assumes 43 seats per bus and a peak-hour factor of 1.00.

The passenger volumes presented in Exhibit 6-17 indicate the number of people that can be carried, assuming uniform flow during the peak-hour (i.e., a peak-hour factor of 1.00). As uniform flow rarely occurs and indicates underservicing of demand when it does occur, appropriate peak-hour factors should be used to reduce these values to design levels to reflect passenger flow variations within the 15-min peak period. Peak-hour factors are discussed in Section 5 of this chapter.

Urban Street Bus Lanes

Exhibit 6-18 shows illustrative urban street bus lane capacities for a *Type 2 bus lane* (i.e., a bus lane where buses can use the adjacent lane to move around stopped traffic or buses) for a range of right-turning traffic and pedestrian crosswalk volumes, applying the conditions shown with the graph to this chapter's capacity methodology. Note that the capacities shown in the graph are based on a single loading area at the critical bus stop. When a bus stop provides multiple loading areas, multiply the capacity value obtained from the graph by the appropriate loading area effectiveness factor from Exhibit 6-63, presented later in Section 5. Capacities of zero shown in the graph are mostly theoretical, as a few turning vehicles ("sneakers") will always complete their turn at the end of the green phase, and may also be allowed to turn right on red, which allows buses to move up in the queue and eventually through the intersection. Nevertheless, low capacities are an indicator that poor bus operations will result.

Exhibit 6-18
Illustrative Urban Street Bus Lane Capacities with One Loading Area



Source: Calculated using this chapter's bus capacity methodology.

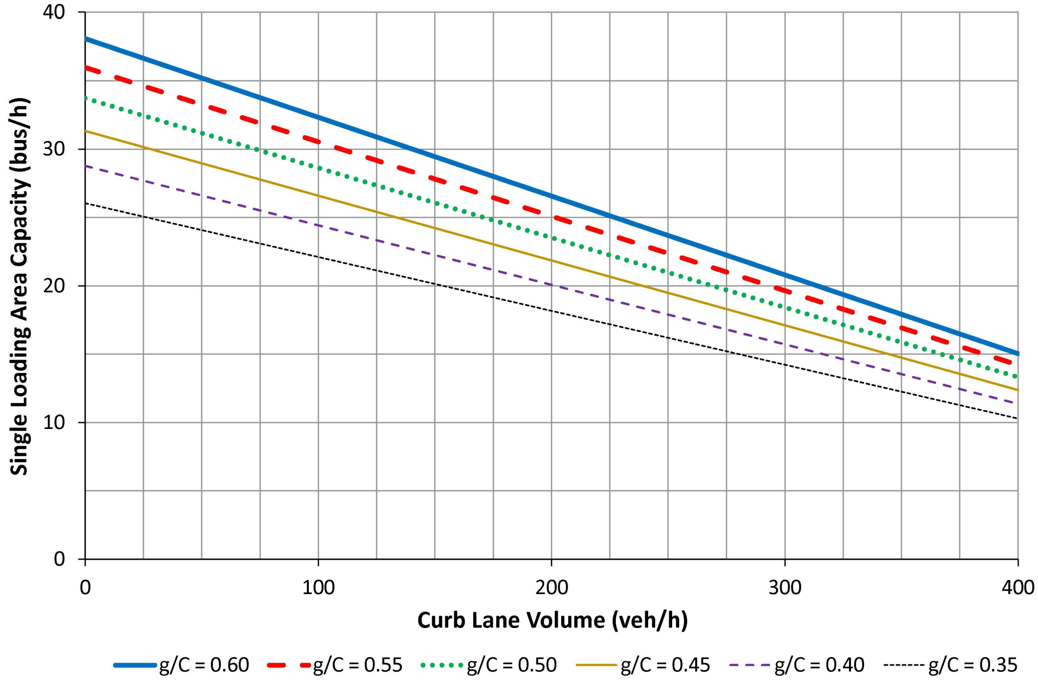
Note: Assumes the following critical bus stop characteristics: Type 2 exclusive bus lane (1 bus lane and at least one general traffic lane in bus' direction of travel), right turns allowed from the bus lane; online, near-side bus stop; 30-s dwell time; 0.6 coefficient of variation of dwell time; g/C = 0.45; and 10% failure rate.

Based on the critical stop having one loading area. Multiply the result from the graph by an appropriate loading area effectiveness value from Exhibit 6-63 for stops with multiple loading areas.

Peds = pedestrians.

Exhibit 6-18 indicates that as either right-turning volumes or pedestrian volumes conflicting with the right turns increase, the number of buses that can be reliably served in an hour by an urban street bus lane drops significantly. The combination of high right-turning volumes and high conflicting pedestrian volumes is especially detrimental to buses, as vehicles turning right from the bus lane must yield to pedestrians, and these vehicles in turn block those buses that not able to move into the adjacent lane. Note also that even when scheduled bus volumes are relatively low, the delaying effect of right-turning traffic will result in lower bus speeds.

Exhibit 6-19
Illustrative Mixed-Traffic Bus Capacities



Source: Calculated using this chapter's bus capacity methodology.

Note: Assumes the following critical bus stop characteristics: Type 2 mixed traffic operation (2+ lanes in bus' direction of travel); online, near-side bus stop; 30-s dwell time; 0.6 coefficient of variation of dwell time; g/C = 0.45; and 10% failure rate.

Based on the critical stop having one loading area. Multiply the result from the graph by an appropriate loading area effectiveness value from Exhibit 6-63 for stops with multiple loading areas.

3. PREFERENTIAL TREATMENTS

OVERVIEW

This section presents information related to the implementation of bus preferential treatments. A wide variety of treatments have been developed in urban areas throughout the world to make bus transit more competitive with the private automobile and to provide a higher quality of service for passengers. This section provides an overview of measures developed as of 2012 that have shown promising operations. In addition, the chapter presents suggested warrants and conditions for applications of priority treatments and provides information of treatment impacts on transit operations.

TCRP Synthesis 83 (*14*) conducted a survey of transit agencies and summarized the application of transit preferential treatments in North America as of 2010 and the warrants specific transit agencies use for application. In addition, it provides a decision-making framework and analysis methods for application of some of the priority treatments addressed in sections 3 and 4. TCRP Project A-39, "Improving Transportation Network Efficiency Through Implementation of Transit-Supportive Roadway Strategies," which had just started at the time of writing, is intended in part to document the effects of various preferential treatments in more detail than the results of previous studies presented in this section (*15*).

Bus Preferential Treatment Uses

A significant amount of delay to transit vehicles in urban areas is caused by traffic congestion. This congestion results in longer travel times for passengers and, over time, requires transit agencies to add more buses to routes in order to maintain headways, which results in higher agency operating costs.

Bus preferential treatments offer the potential to reduce the delays experienced by buses operating in mixed traffic. These measures are aimed at improving schedule adherence and reducing travel times and delays for transit users. The measures may attract new riders, increase transit capacity, and improve the transit quality of service.

Bus preferential treatments seek to offset the delays caused by traffic.

Successful priority measures are usually characterized by (*14*):

- An intensively developed downtown area with limited street capacity and high all-day parking costs,
- A long-term reliance on public transportation,
- Highway capacity limitations on the approaches to downtown,
  - Major water barriers that limit road access to the downtown and channel bus flows,
  - Fast non-stop bus runs for considerable distances,
  - Bus priorities on approaches to or across water barriers,
  - Special bus distribution within downtown (often off-street terminals), and
  - Active traffic management, maintenance, operations, and enforcement programs.

Transportation policies that give priority to transit vehicles because of their efficiency benefits may allow transit agencies to implement transit priority measures.

Bus preferential treatments defined.

Bus preferential treatments can be generally defined as a range of techniques designed to speed up transit vehicles and improve overall system efficiency. They include physical improvements, operating changes, and regulatory changes. Bus preferential treatments may reduce travel time variability and improve schedule adherence, depending on the application. When considering implementing these treatments, the total change in person delay (including both passengers in buses and in private vehicles) should be taken into account. Local, regional, or state transportation policies favoring particular travel modes in particular situations may expand or limit the potential for application outlined in this chapter.

Where there has been a strong policy directive to improve the role of public transit in accommodating a community's travel needs, preferential treatments should be implemented with transit agency and traffic engineering agency staff working in a coordinated manner. Measures should be cost effective and should consider both long-term changes to mode split and the potential for attracting new riders. Both of these factors may be difficult to quantify. In most cases, bus preferential treatments will be more acceptable to roadway users and decision makers when improvements to transit operations do not create undue traffic disruptions. However, in a policy environment favoring transit usage over private automobiles, investments in bus preferential treatments rather than expanded roadway capacity may be seen as a means of further improving transit attractiveness and maximizing roadways' person-carrying ability.

In situations where the policy direction is not as clear or the inter-agency working relationships are not as strong, an incremental approach to developing preferential treatments may be more successful. This approach could involve demonstration projects that have a good potential for success and could be used to develop support for broader transportation improvement projects in the future.

Bus preferential treatments can provide a cost effective way of improving transit service based on focused, one-time capital investments as opposed to increased service that requires annual operating funding. They offer the potential for reducing or postponing the need for added service to respond to congestion and can attract new riders to transit, if the treatments provide a noticeable improvement in travel time, service reliability, or both.

Person Delay Considerations

The net change in person delay is an important factor to consider before implementing transit priority measures.

In many cases, providing bus preferential treatments involve trade-offs among the various users of a roadway facility. Providing a bus queue jump at a traffic signal, for example, provides a time-savings benefit for bus passengers, while possibly causing additional delay for motorists, their passengers, bicyclists, and some pedestrians. When considering implementing a preferential measure, one factor to consider should be the net change in person delay to all roadway users as a result of the measure. Of course, other factors such as cost, change in transit quality of service, and local policies encouraging greater transit use should also be considered.

BUSWAYS AND FREEWAY MANAGED LANES

Facilities that provide segregated rights-of-way for buses offer a number of advantages that can improve service quality. Bus travel times, schedule adherence, and vehicle productivity are improved when buses are able to use higher-speed, uncongested facilities. These improvements, in turn, promote efficiency, improve reliability, and increase the potential to gain new riders. However, these facilities often require capital and operating (maintenance) expenditures on the part of the transit agency that are not incurred when buses operate on public roadways.

Busways and freeway managed lanes are the facility types offering segregated rights-of-way. Transit industry use of the terms *busway* and *transitway* is inconsistent, with the two terms often used interchangeably. The term *busway* has been used to describe facilities ranging from bus lanes in the medians of urban streets, to exclusive bus roads with at-grade intersections, to freeway managed lanes used exclusively by buses, to Ottawa-style grade-separated bus facilities with rail-like infrastructure. The TCQSM uses the terms *median busway, at-grade busway, freeway managed lanes,* and *grade-separated busway,* respectively, to describe these facility types.

Industry usage of the terms transitway *and* busway *is not consistent, and the terms are often used interchangeably.*

In North America, busways and freeway managed lanes are found mainly in larger cities, usually with a large downtown employment and heavy peak-hour bus ridership. However, these facilities have found application internationally as a substitute for, or supplement to, rail systems. When facilities are located on exclusive rights-of-way, they may not be easy to walk to. In these cases, most ridership stems from park-and-ride lots located along the facilities, from transfers from other routes, or from buses using the facilities after circulating through a neighborhood.

Operational Overview

At-grade busways in North America include the 8-mi (13-km) South Dade Busway in Miami; the 15-mi (24- km) Orange Line in Los Angeles; the median busway portion of the Euclid corridor in Cleveland; and portions of the Franklin corridor in Eugene, Oregon. Median busways are used in a number of South American cities, including Belo Horizonte, Curitiba, Porto Alegre, and São Paulo, Brazil; Bogotá, Colombia; and Quito, Ecuador. Median busways are also planned as part of new or enhanced BRT routes in Los Angeles; San Francisco; Montgomery County, Maryland; and Washington, D.C.

At-grade busways, including median busways.

Exhibit 6-20 shows examples of at-grade busway stations that utilize level boarding and pre-paid fares. The Cape Town BRT station shown in Exhibit 6-20(a) provides high-level boarding (with platform screens to prevent passengers from entering the busway) and passengers pay their fare on entering the station building. The Eugene BRT station shown in Exhibit 6-20(b) provides level boarding onto a low-flow bus, with fares bought from a machine on the platform and fares randomly inspected on board. Both types of designs allow boarding passengers to utilize all bus doors which, when combined with the level boarding, allows large volumes of passengers to board and alight in a relatively short time, resulting in relatively low dwell times and improved bus speeds.

Exhibit 6-20
At-Grade Busway Station Examples

(a) Cape Town

(b) Eugene

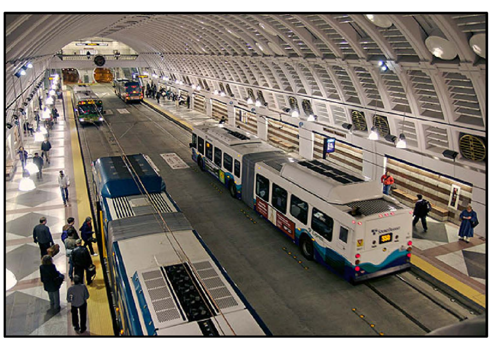
Busways and freeway managed lanes separate buses from other traffic, which reduces the potential for conflicts that result in delays. In some cases, operating speeds may increase significantly with the use of freeway facilities; in others, the savings are less dramatic. After managed lanes were opened along several freeways in Houston, peak-hour bus operating speeds increased from 26 to 51 mi/h (42 to 83 km/h) (*16*).

Effective distribution of buses within downtown areas remains a challenge. Freeway-related treatments generally provide good access to the downtown perimeter, but do not substantially improve service within the downtown core. Furthermore, transit terminals are not always located near major employment locations, and may require secondary distribution. However, other means exist to continue to favor bus movements once buses enter the downtown street network (*17*).

Bus tunnels.

A capital-intensive solution to downtown bus distribution, a 1.3-mi (2.1-km), five-station bus tunnel (Exhibit 6-21a), opened in Seattle in 1991. Bus routes using the tunnel (now combined with light rail transit operations) are operated with a special fleet of dual-mode buses that run on overhead electric power in the tunnel and diesel power on the surface portions of their routes. Both ends of the tunnel connect to freeway ramps; the south end via an at-grade busway. Boston's Silver Line BRT route has a 1.0-mi (1.6-km), three-station tunnel used by dual-powered buses (Exhibit 6-21b), and plans an additional 1.0-mi (1.6-km), two-station extension in the future. Some bus routes in Providence use a former streetcar tunnel that has been converted to bus use, and busways in Brisbane, Australia also have tunnel sections.

Exhibit 6-21
Bus Tunnel Examples



(a) Seattle

(b) Boston

Impacts on Bus Operations

Exhibit 6-22 presents typical impacts of preferential treatments on freeway bus operations.

Exhibit 6-22
Typical Impacts of Busways and Freeway Managed Lanes on Bus Operations

Treatment	Travel Time Improvements	Person Delay Impacts	Additional Considerations
Busways	Up to 10 percent; varies depending on routing and other design details	Minimal to significant, depending on the project	Applications include special detection technologies that distinguish buses from general traffic
HOV lanes	Up to 20 percent; varies on out of direction travel	Significant, dependent on application	
Freeway bus lanes	3–15% of overall travel time, up to 75% of delay	Minimal to significant, highly dependent on the strategy and location	Travel time improvements are a function of the existing delay
Bus lane bypasses	Up to 20%; up to 90% of ramp meter delay	Potentially significant	Potential disruptions to queue storage needs on ramps

Sources: *NCHRP Synthesis 185* (*19*), *TCRP Web-Only Document 12* (*20*), and *TCRP Report 26* (*21*).
Note: HOV = high-occupancy vehicle.

Typical Conditions for Application

Policy and cost considerations usually dictate the lower limit for bus volumes that warrant busway or freeway managed lane treatments. Lower minimum vehicle thresholds can be expected, and are usually accepted, with busways than with freeway facilities; however, the minimum vehicle threshold may be higher in a heavily congested corridor than in one with lower levels of congestion. Non-users in heavily congested areas may be much more vocal about a facility they feel is underutilized than commuters in a corridor where congestion is not at serious levels. Whenever considering providing busway or high-occupancy vehicle (HOV) facilities, the perceptions of commuters and the public, as well as any unique local conditions, should be considered when developing minimum operating thresholds (*18*).

Exhibit 6-23 presents typical minimum freeway managed lane operating thresholds in vehicles per hour per lane (combined bus and HOV volumes), based on U.S. experience. These thresholds balance the number of people using the lane with the cost of constructing the lane.

Exhibit 6-23
Typical Freeway Managed Lane Minimum Operating Thresholds

Facility Type	Minimum Operating Threshold (veh/h/lane)
Separate right-of-way, HOV	800–1,000
Freeway, exclusive two-directional	400–800
Freeway, exclusive reversible	400–800
Freeway, concurrent flow	400–800
Freeway, contraflow HOV	400–800
HOV queue bypass lanes	100–200

Source: *NCHRP Report 414* (*18*).
Note: Volumes include both buses and private vehicles that are HOVs.

Exhibit 6-24 presents planning guidelines for minimum bus or passenger volumes for busways and bus priority treatments associated with freeways. These guidelines balance the number of people using the facility with the cost of constructing the facility and the perceived usage of the facility by non-users.

Exhibit 6-24
General Planning Guidelines for Busways and Freeway Managed Lanes

Treatment	Minimum One-Way Peak Hour Volumes: Bus	Minimum One-Way Peak Hour Volumes: Passenger	Related Land Use and Transportation Factors
Exclusive busways on special right-of-way	40–60	1,600–2,400	Urban population: 750,000; CBD employment: 50,000; 1.85 million m^2 CBD floor space; congestion in corridor; save buses 1+ min/mi (0.6+ min/km).
Exclusive busways within freeway right-of-way	40–60	1,600–2,400	Freeways in corridor experience peak-hour congestion; save buses 1+ min/mi (0.6+ min/km)
Busways on railroad right-of-way	40–60	1,600–2,400	Potentially not well located in relation to service area. Stations required.
Freeway bus lanes, normal flow	60–90	2,400–3,600	Applicable upstream from lane drop. Bus passenger time savings should exceed other road user delays. Normally achieved by adding a lane. Save buses 1+ min/mi (0.6+ min/km).
Freeway bus lanes, contraflow	40–60	1,600–2,400	Freeways with six or more lanes. Imbalance in traffic volumes permits freeway LOS D in off-peak travel direction. Save buses 1+ min/mi (0.6+ min/km).
Bus lane bypasses at toll plazas	20–30	800–1,200	Adequate queuing area on toll plaza approach, so bus lane access is not blocked.
Exclusive bus access to non-reserved freeway or arterial lane	10–15	400–600	
Bus bypass lane at metered freeway ramp	10–15	400–600	Alternate surface street route available for metered traffic. Express buses leave freeways to make intermediate stops.
Bus stops along freeways	5–10	50–100*	Generally provided at surface street level in conjunction with metered ramp.

Source: Levinson, Adams, and Hoey (*17*).
*Boarding or alighting passengers in the peak hour.

Freeway Managed Lanes

When the term is used in the TCQSM, "managed lane" implies buses may always use the lane and that other vehicle types may be allowed to use the lane.

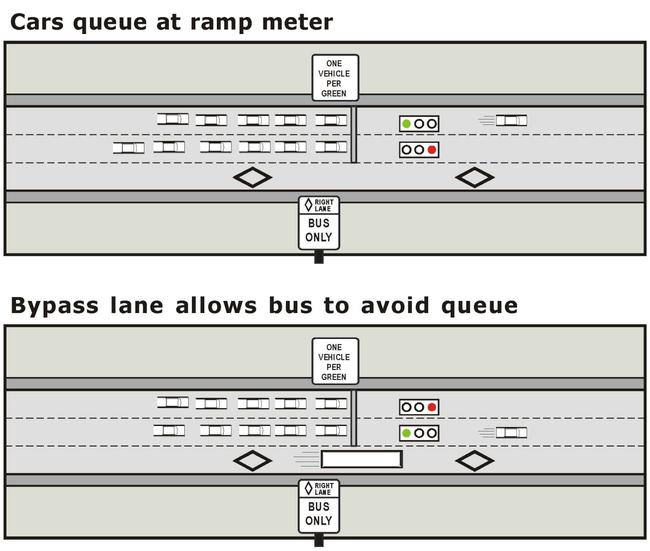
In its most broad usage, a managed lane is a lane that is restricted to a particular type of vehicle—for example, buses, trucks, vehicles paying tolls to use the lane, or vehicles occupied by a given number of people (usually two or three). These lanes can be immediately adjacent to regular traffic lanes, separated from other traffic by a painted median or removable pylons, or completely separate and protected from other traffic by physical barriers (*23*).

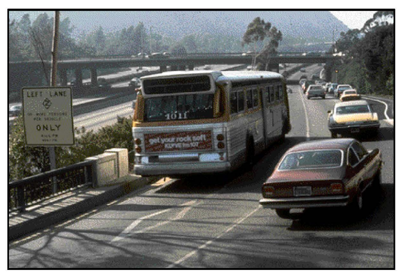
Houston's managed lane system, illustrated in Exhibit 6-25, is the most extensive deployment of managed lanes in North America. The lanes were constructed originally for buses (also used by carpools and vanpools); in 2002, these lanes saved the average commuter 12 to 22 min per trip (*16*). Most of these lanes were converted into high-occupancy toll (HOT) lanes between 2009 and 2012. During peak periods, drivers without passengers are allowed to use the managed lanes by paying a toll. Tolls are based on time of day and the congestion level of the managed lanes. Tolls are paid electronically though an authorized toll tag. Traffic monitoring systems help maintaining traffic speed on the managed lanes to ensure optimal travel times.

Exhibit 6-25
Houston Freeway Managed Lane Example

Freeway Ramp Queue Bypasses

Queue bypasses are a form of priority treatment that allows buses to avoid queues of vehicles (such as those that develop at freeway ramp meters) by providing a short managed lane that avoids the queue. This form of bus priority often involves considerable innovation to find methods of enabling buses to avoid recurring congestion. Exhibit 6-26 depicts a typical queue bypass design on a freeway on-ramp, along with actual applications.





Source: TCQSM 2nd Edition (*5*).

Exhibit 6-26
Freeway Ramp Queue Bypasses

Top right: Los Angeles
Bottom right: The Netherlands

Shoulder Use

In some metropolitan areas—Minneapolis being the best example (Exhibit 6-27)—buses are allowed to use the paved shoulder to bypass congestion in the general traffic lanes on freeways and multilane highways. As a result, bus travel is faster and more reliable than travel in the general traffic lanes. Bus shoulder use is typically considered when (*22*):

- Roadways are congested during peak periods (speeds less than 35 mi/h or 55 km/h);

- Insufficient space or bus volumes exist to add a managed lane;
- Four to six buses or more an hour use the freeway;
- At least 10-ft (3-m) shoulder width is provided—preferably at least 11.5 ft (3.5 m) on long overpasses and 12 ft (3.7 m) or more when higher speed differentials between buses and general traffic are desired; and
- The shoulder is strong enough to support regular bus use.

The use of auxiliary (i.e., exit-only) lanes at freeway off-ramps, shared right-turn lanes at signalized intersections on highways, and ramp metering on freeway on-ramps helps facilitate merging and weaving movements between buses and other vehicles entering and exiting the highway. Buses are typically limited to traveling no more than 10 to 15 mi/h (15 to 25 km/h) faster than adjacent traffic, but even these speed differentials can result in significant time savings over extended distances. *TCRP Report 151: A Guide to Implementing Bus on Shoulder (BOS) Systems* provides case studies of bus use of shoulder lanes and guidance for implementing them (*22*).

Exhibit 6-27
Examples of Bus on Shoulder Operation (Minneapolis)

(a) Freeway

(b) Multilane highway

URBAN STREET BUS LANES

Arterial street bus lanes provide segregated rights-of-way for buses. Because these facilities have *interrupted flow* (e.g., traffic signals), due to intersections with other streets, they provide a lower level of priority to transit than facilities on exclusive rights-of-way. Nevertheless, arterial street bus lanes offer buses significant advantages over mixed-traffic operations. Exhibit 6-28 lists common sources of delays to buses operating in mixed traffic that bus lanes and site-specific preferential treatments help overcome. These delays reduce bus capacity, speed, and reliability, resulting in reduced service quality for passengers and potentially increased operating costs for transit agencies.

Exhibit 6-28
Sources of Delay for Buses Operating in Mixed Traffic at Intersections

Intersection Type	Delay Sources
Signalized	Insufficient traffic signal green time for bus approach Poor signal progression for buses Inadequate vehicle detection at signals
All	Queued vehicles on intersection approach On-street parking maneuvers Inadequate lane width Off-line bus stop reentry delay Right-turning traffic blocking access to stop Left-turning traffic blocking shared lane

Bus lanes can be created by several means:

- Redesignating an existing travel lane as a bus lane,
- Narrowing existing lanes to provide an additional lane,
- Widening the street to add a new lane, and
- Restricting on-street parking (part-time or full-time) to provide a bus lane.

Where there is a relatively high volume of buses operating on a roadway, coupled with significant bus and automobile congestion, exclusive bus lanes can provide more attractive and reliable bus service. Most bus lanes take the form of reserved lanes on city streets, usually in the same direction as the general traffic flow. However, some cities provide bus-only streets, such as 16th Street in Denver, the Nicolet Mall in Minneapolis, the 5th and 6th Avenue transit mall in Portland (where buses now share the roadway with light rail transit), and the Granville Mall in Vancouver.

Exhibit 6-29 shows applications where (*a*) on-street parking was removed and existing lanes narrowed to create a bus lane, and (*b*) parking is restricted during peak periods to provide a bus lane.

Exhibit 6-29
Bus Lane Development via Parking Restrictions

(a) Full-time lane (Portland)

(b) Part-time lane (Seattle)

Median Busway

Description

Median busways are exclusive bus lanes located in the median of an urban street. These facilities require dedicated ROW sufficient for the running way and stations. The median busway interfaces with general traffic at signalized intersections where cross streets are allowed to cross the busway. Left-turn lanes and protected left-turn signal phasing (i.e., left-turn arrows) are provided on the main street to facilitate left- and U-turns across the busway. Unsignalized minor intersections and local drive ways along the transitway are restricted to right-turn movements in and out.

Station platforms are implemented within the ROW, preferably on the far side of signalized intersections, as this location facilitates the application of transit signal priority and preserves ROW (one station and one general traffic left-turn lane for the opposite direction can be paired on each side of the intersection). Stations are typically located on the right side in the U.S. because doors are located on the right side of the bus. Stations designed with center platforms serving both directions require special buses equipped with doors on both sides, as are used on BRT routes in Cleveland and Eugene (Exhibit 6-30).

Exhibit 6-30
Median Busway Center Station Examples

(a) Cleveland (b) Eugene

Some form of physical barrier, such as jersey barriers, curbing, or raised pavement markers, is typically used to separate the median busway from general traffic and to prevent pedestrians crossing the transitway. In addition, signage (DO NOT ENTER and PEDESTRIANS AND BICYCLES PROHIBITED) at intersections indicates designated transit use.

Typical Conditions for Application

NCHRP Report 155: Bus Use of Highways—Planning and Design Guidelines (*17*) defines warrants for median bus lanes as 60 to 90 one-way buses per peak hour, with a minimum bus volume of 600 per day, based on providing sufficient usage to make the bus lanes appear used (e.g., 60 buses per hour is equivalent to an average of one bus per minute). However, the North American median busways that had been developed as of 2012 served far fewer buses per hour, having been developed for policy reasons (e.g., to encourage a mode shift to transit) and with a vision of preserving the enhanced bus speed, reliability, and capacity provided by the busway for the long term in the face of increasing traffic congestion.

Median busways require sufficient ROW to accommodate adequately sized station platforms, the bus running way, left-turn lanes at signalized intersections, along with sufficient additional ROW to accommodate other road users (e.g., motorized vehicles, bicyclists, and pedestrians). Providing passing lanes at stations requires additional ROW, but provides operational flexibility to operate a mix of limited-stop and all-stop services along the busway. *TCRP Report 90: Bus Rapid Transit, Volume 2: Implementation Guidelines* (*24*) presents the range of costs for constructing new bus lanes; *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic* (*14*) estimates their operating and maintenance costs to be modest.

Exclusive Bus Lanes

Exclusive bus lanes are developed along a roadway by widening or dedicating one or more existing general traffic or parking lanes for transit use. They can be peak period only, or all day. These lanes typically allow use by general traffic for turning movements at intersections and driveway. There are four kinds of exclusive bus lanes:

- Concurrent flow,
- Contraflow,
- Bi-directional, and
- Intermittent.

Concurrent-Flow Lanes

A concurrent-flow lane is a lane designated for transit vehicles moving in the same direction as general traffic. In some cases, carpools and vanpools are also allowed to use the lane. The lane can be located:

1. On the right side, adjacent to the curb or shoulder.
    a. If there is on-street parking, this configuration requires the removal of parking, either permanently or during the hours of exclusive bus use.
    b. Right-turn and local access driveway traffic are allowed to use the lane over short distances.
    c. Enforcement (e.g., ticketing and/or towing stopped and parked vehicles), public education, signing , and pavement markings are required to maintain the exclusivity of the bus lane and to preserve the desired bus speed, reliability, and capacity benefits.
2. On an *interior* or *offset* bus lane that operates adjacent to the curb lane.
    a. This configuration leaves the curb lane available for other uses, including parking, loading, and right-turn movements.
    b. An interior transit lane has a significant impact on the travel capacity of the street since one general purpose lane was converted into a transit-only lane. However, parallel streets may be able to absorb diverted automobile traffic.

Concurrent-flow lanes can be developed in a variety of configurations (*14*):

- One permanent lane in each direction of travel;
- One part-time lane operating in the peak direction during its peak period, with another part-time lane serving the opposite direction during its peak period;
- One single lane operating in one direction during one time period, then reversed to operate in the opposite direction during another time period (i.e., a reversible lane); and
- Two permanent or part-time lanes in each direction of travel, providing added capacity and bus stop bypassing capability when bus volumes are high and multiple routes use the facility.

Exhibit 6-31 shows examples of different types of exclusive bus lanes.

Exhibit 6-31
Exclusive Bus Lane Examples

(a) Curbside bus lane with right-turn lane (Copenhagen)

(b) Interior bus lanes (Boston)

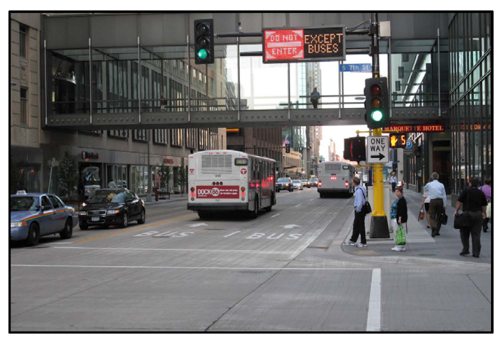
(c) Dual bus lanes (New York)

Contraflow Lanes

Contraflow lanes (Exhibit 6-32) are designated exclusive bus lanes that operate in the opposite direction of general traffic. They are developed almost exclusively on one-way streets. Special signage, physical barriers, and/or lane use control signals are used to alert other roadway users of the directional of use of the lane.

Exhibit 6-32
Contraflow Lane Examples

(a) Orlando



(b) Minneapolis

Bi-directional Lanes

Bi-directional transit lanes may be used when there is only enough right-of-way to implement a single dedicated bus lane. Their length is desirably no more than two to three signalized intersections, as they can only serve one direction of bus travel at a time. The longer the bi-directional section, the longer minimum headway between buses traveling in the same direction through the section, when opposite directions of travel are served alternately. Nevertheless, bi-directional lanes can provide a higher level of reliability compared to congested mixed-traffic operation over the same section.

Bi-directional operation requires advanced signal systems to control bus movement through the section and special signing and pavement markings to alert other roadway users to the bi-directional operation. Stops or stations within a bi-directional section desirably provide lanes for both directions of travel at the station (allowing buses traveling in opposite directions to meet and pass each other); otherwise, separate stations need to be provided for each direction of travel (if buses only have doors on the right side) or buses must have doors on both sides (if one station is to serve both directions from a single bus lane). Exhibit 6-33 illustrates bi-directional operation.

Exhibit 6-33
Bi-directional Operation Example (Eugene)

Intermittent Lane

An intermittent, or moving, bus lane relies on technology and enforcement to provide bus priority. A segment of a general-purpose lane turns into a bus lane before a bus arrives and reverts back to general-purpose operation once a bus has passed. From the bus's point-of-view, the bus receives an exclusive lane continuously as it progresses down a street. Any given section of the lane is restricted to bus-only use only for the short period of time when a bus is present. This approach to bus priority might be useful where bus service is relatively infrequent and traffic-related bus delays are high, but sufficient capacity exists for other vehicles to move out of the bus lane when needed. As bus frequencies increase, a permanent bus-only lane may be considered.

An intermittent lane requires a combination of several technologies:

- Roadway sensors monitor traffic conditions (flow, speed, and queues) in real time;
- An AVL system monitors bus's positions in real time;
- A prediction algorithm estimates a bus's arrival time to the next segment, as well as the time needed for traffic already in the lane to continue forward to empty out of the segment that is about to turn into a bus lane; and
- Variable message signs and flashing lights installed in the pavement along the lane divider communicate to motorists that a bus is approaching and that they must exit the lane.

For this priority treatment approach to be effective, driver education and enforcement are paramount. As of 2012, there were no applications of these bus lanes in North America, although mixed light rail–bus operation along Portland's 5th and 6th Avenue transit mall provides intermittent priority for light rail trains in the left-hand transit lane, requiring buses not to use the lane when a train approaches. A demonstration project of an intermittent bus lane, using overhead signage and an in-pavement lighting system, was conducted in Lisbon (*25*).

Typical Conditions for Bus Lane Application

Bus lanes have been provided on urban streets by adding lanes, developing contraflow lanes, and converting roadway shoulders for bus use. Factors that influence whether bus lanes may be appropriate include (*21*):

- Congestion,
- Travel time savings,
- Person throughput,
- Vehicle throughput,
- Local agency support,
- Enforceability, and
- Physical roadway characteristics.

Policy and cost considerations generally set the lower limit for bus volumes that warrant priority treatments on urban streets, while bus vehicle capacity sets the upper limit. The procedures presented later in this chapter can be used to determine the design capacity of a bus lane based on specific local conditions. In addition, a variety of studies have developed planning guidelines for minimum and maximum bus volumes for bus lanes, which are summarized below.

A study of bus operations in Manhattan recommended the following desirable maximum a.m. peak-hour bus volumes for arterial street bus lanes (*26*):

- Two lanes exclusively for buses: 180 bus/h;
- One lane exclusively for buses, partial use of adjacent lane: 100 bus/h;
- One lane exclusively for buses, no use of adjacent lane: 70 bus/h; and
- Buses in curb lane in mixed traffic: 60 bus/h.

Exhibit 6-34 presents general planning guidelines for bus preferential treatments on arterial streets. A comparison of person volumes on buses operating in mixed traffic with person volumes in other vehicles operating on the street can also be used to help decide when to dedicate one or more lanes to exclusive bus use.

Exhibit 6-34
General Planning Guidelines for Bus Lanes on Urban Streets

Treatment	Minimum One-Way Peak-Hour Volume		Related Land Use and Transportation Factors
	Bus	Passenger	
Bus streets or malls	80–100	3,200–4,000	Commercially oriented frontage.
CBD curb bus lanes, main street	50–80	2,000–3,200	Commercially oriented frontage.
Curb bus lanes, normal flow	30–40	1,200–1,600	At least 2 lanes available for other traffic in same direction.
Median bus lanes	60–90	2,400–3,600	At least 2 lanes available for other traffic in same direction; ability to separate vehicular turn conflicts from buses.
Contraflow bus lanes, short segments	20–30	800–1,200	Allow buses to proceed on normal route, turn around, or bypass congestion on bridge approach.
Contraflow bus lanes, extended	40–60	1,600–2,400	At least 2 lanes available for other traffic in opposite direction. Signal spacing greater than 500-ft (150-m) intervals.

Sources: Levinson, Adams, and Hoey (*17*) and *NCHRP Report 414* (*18*).

TCRP Report 118: Bus Rapid Transit Practitioner's Guide (*11*) presents additional guidance for the operation of exclusive bus lanes:

1. Concurrent-flow lanes may operate along the outside curb, in the lane adjacent to a parking lane (interior lane), or in a paved median area (without a dedicated median transitway).
2. Concurrent-flow lanes can operate at all times, for extended hours (e.g., from 7 a.m. to 7 p.m.), or just during peak hours.
3. Contraflow lanes should operate at all times.
4. Under conditions of heavy bus volumes, dual concurrent-flow or contraflow lanes may be desirable.
5. Where the bus lanes operate at all times, special colored pavement may be desirable to improve the identity of the BRT operations.
6. Bus lanes should be at least 11 ft wide to accommodate an 8.5-ft bus width.
7. The bus lanes should carry as many people as in the adjacent general traffic lane. Generally, at least 25 buses should use the lanes during the peak hour. (Ideally, there should be at least one bus per signal cycle to give buses a steady presence in the bus lane.) There should be at least two lanes available for general traffic in the same direction, wherever possible. (However, many European bus lane installations leave only one lane for general traffic.)
8. Parking should be prohibited where bus lanes are along the curb, but it may remain where interior bus lanes are provided.
9. There should be suitable provisions for goods delivery and service vehicle access, either during off-hours or off-street.

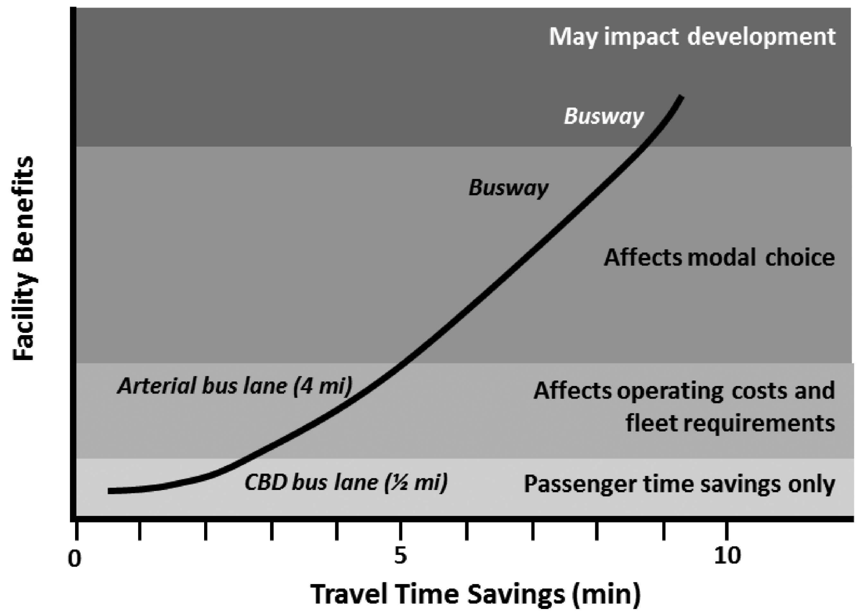
Impacts of Median Busways and Exclusive Bus Lanes on Bus Operations

The primary benefits of median busway and exclusive bus lane operations over mixed-traffic operations are (*a*) reduced conflict with general traffic, resulting in reduced transit travel time, and (*b*) improved transit reliability. In addition, secondary benefits may result depending on the amount of travel time saved, as illustrated in Exhibit 6-35:

- Small amounts of travel time savings primarily benefit passengers.
- As the travel time savings increase, transit fleet requirements and thus operating costs may be reduced.

Travel time savings of more than 5 min (on a typical trip) can affect mode choice and increase ridership. High travel time savings possibly contribute to changes in land development patterns.

Exhibit 6-35
Degree of Bus Lane Impacts



Source: Adapted from *TCRP Report 26* (*21*).

Exhibit 6-36 provides examples of travel time savings documented on urban street bus lanes.

Exhibit 6-36
Observed Travel Time Savings with Urban Street Bus Lanes

City	Street	Travel Time Savings
Los Angeles	Wilshire Boulevard	0.1–0.2 min/mi (a.m.) 0.5–0.8 min/mi (p.m.)
Dallas	Harry Hines Boulevard	1 min/mi
Dallas	Ft. Worth Boulevard	1.5 min/mi
New York	Madison Avenue (dual bus lanes)	43% express bus 34% local bus
San Francisco	1st Street	39% local bus

Sources: *TCRP Report 26* (*21*); *TCRP Report 90, Volume 2* (*24*); and *TCRP Report 118* (*11*).

Exhibit 6-37 shows observed reliability improvements associated with urban street bus lanes. The improved reliability is measured by the percent change in the coefficient of variation of travel time (standard deviation divided by the mean).

Exhibit 6-37
Observed Reliability Improvements with Urban Street Bus Lanes

City	Street	Percent Improvement*
Los Angeles	Wilshire Boulevard	12–27
New York	Madison Avenue (dual bus lanes)	11 (express buses) 31 (local buses)

Sources: *TCRP Report 26* (*21*) and *TCRP Report 118* (*11*).
* Percent change in the coefficient of variation of travel time.

TRANSIT SIGNAL PRIORITY (TSP)

Overview

TSP alters traffic signal timing at intersections to give priority to transit operating in a median busway, in exclusive bus lanes, or in mixed traffic. TSP modifies the normal signal operation to better accommodate transit vehicles while maintaining signal coordination along a route and overall signal cycle length at individual intersections.

Early attempts to provide signal priority were based on signal *preemption*, where buses were given a nearly immediate green signal, regardless of other conditions, in the same manner that emergency vehicles and railroad trains are able to pre-empt traffic signals. Signal preemption is generally not desirable from a traffic signal control system standpoint and because it raises potential pedestrian crossing safety issues, it has been dismissed by most roadway agencies. Current practice is to provide signal *priority*, where providing preferential treatment for buses is balanced against other system needs.

Signal priority is different than preemption, which is normally associated with emergency vehicles and railroad crossing operations.

Signal priority measures include passive, active, and real-time priority. *Passive* strategies attempt to accommodate transit operations through the use of pre-timed modifications to the signal system that occur whether or not a bus is present to take advantage of the modifications. These adjustments are completed manually to determine the best transit benefit while minimizing the impact to other vehicles. Passive priority can range from simple changes in intersection signal timing to systemwide retiming to address bus operations. Passive strategies can utilize transit operations information, such as bus travel times along street segments, to determine signal timing coordination plans.

Reducing the traffic signal cycle length on an arterial or downtown grid system is a passive priority measure.

Active strategies adjust the signal timing after a bus is detected approaching the intersection. Depending on the application and capabilities of the signal control equipment, active priority may be either conditional or unconditional. *Unconditional* strategies provide priority whenever a bus arrives. *Conditional* strategies incorporate information from onboard automatic vehicle location (AVL) equipment (e.g., whether or not the bus is behind schedule, and by how much), and/or automatic passenger counter (APC) equipment (e.g., how many people are on board), along with signal controller data on how recently priority was given to another bus at the intersection, to decide whether or not to provide priority for a given bus (*27*).

Conditional strategies can incorporate information on bus schedule status, loading, and recent requests for priority to determine whether or not to grant priority to a given bus.

Real-time strategies consider both automobile and bus arrivals at a single intersection or a network of intersections. Applications of real-time control have been limited to date and require specialized equipment that is capable of optimizing signal timings in the field to respond to current traffic conditions and bus locations.

Exhibit 6-38 summarizes common bus signal priority treatments.

Exhibit 6-38
Types of Bus Signal Priority Systems

Treatment	Description
	PASSIVE PRIORITY
Adjust cycle length	Reduce cycle lengths at isolated intersections to benefit buses
Split phases	Introduce special phases at the intersection for the bus movement while maintaining the original cycle length
Areawide timing plans	Preferential progression for buses through signal offsets
Bypass metered signals	Buses use special reserved lanes, special signal phases, or are rerouted to non-metered signals
Adjust phase length	Increased green time for approaches with buses
	ACTIVE PRIORITY*
Green extension	Increase phase time for current bus phase
Early start (red truncation)	Reduce other phase times to return to green for buses earlier
Special phase	Addition of a bus phase
Phase suppression	Skipped non-priority phases
	REAL-TIME PRIORITY*
Delay-optimizing control	Signal timing changes to reduce overall person delay
Network control	Signal timing changes considering the overall system performance
	PREEMPTION*
Preemption	Current phase terminated and signal returns to bus phase

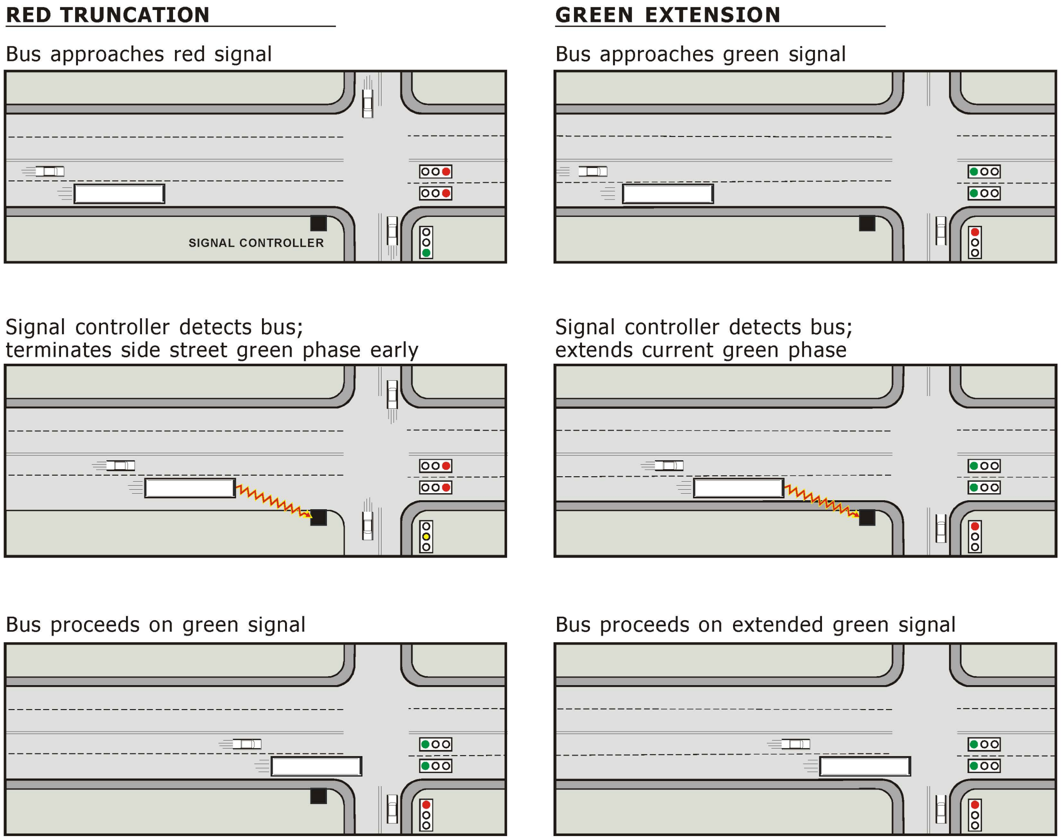
Source: Bullard and Nungesser (*28*).

Note: *Any of the listed treatments can be unconditional (occur whenever a request is received) or conditional (priority is granted if other conditions—schedule status, loading, etc.—are met).

TSP treatment is a minor adjustment to signal phase split times. The green indication facing an approaching bus may stay green longer—*green extension*—or start sooner—*red truncation.* The intent is to eliminate or reduce delay to buses at signalized intersections. The additional time given to or taken away from a particular phase is usually no more than 10% of the signal cycle, and is recovered during the following signal cycle(s) so that traffic signal coordination can be maintained along the street. The decision whether TSP is granted can be made locally at the individual intersections, or at a traffic management center coordinating multiple intersections or entire routes. TSP can be applied as a separate preferential treatment or in combination with other physical and operational treatments, such as exclusive lanes and stop consolidation.

Exhibit 6-39 illustrates the red truncation and green extension process associated with an active signal priority implementation. In this exhibit, street-side equipment detects the bus (for example, using a transponder or an optical system), while bus-mounted equipment transmits a request for priority to the signal controller. As discussed later, other methods of monitoring a bus's location relative to an intersection are also feasible.

Exhibit 6-39
Bus Signal Priority Concept—Red Truncation and Green Extension



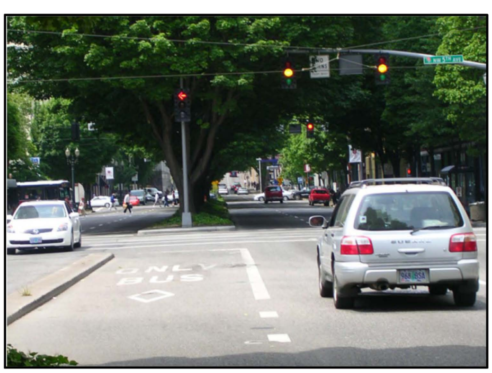
Source: TCQSM 2nd Edition (*5*).

The importance of the relationship between transit staff and traffic engineering staff cannot be overemphasized. Coordination between these groups is necessary for effective implementation of transit priority measures.

Special Signal Phasing

Another signal preferential treatment strategy is to introduce a transit-only signal or added signal phase into an intersection. This approach typically provides a special left-turn signal at a particular location to allow buses to make turns onto a cross street. Exhibit 6-40 shows two examples of this kind of treatment, (*a*) a bus-only left-turn lane accessed from a general purpose lane and (*b*) a special signal phase allowing left, through, and right bus movements from right-side bus lanes. A bus-only left-turn lane combined with a bus stop in the street median is another possibility.

Exhibit 6-40
Special Bus Left-Turn Phasing Examples



(a) Bus-only left-turn lane (Portland)

(b) Left turn from right-side bus lane (Vancouver)

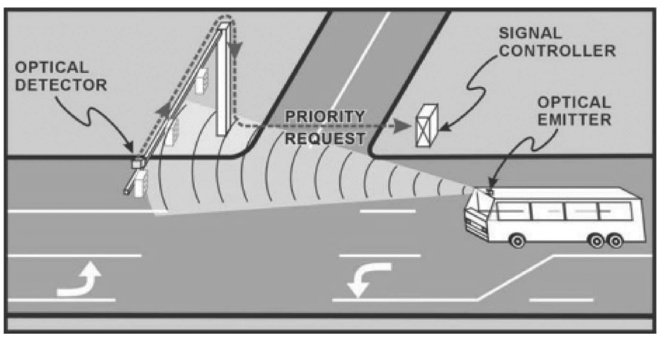
TSP Technology

Signal priority systems vary in complexity. Simple systems that rely on bus operator intervention reduce the amount of on-vehicle technology that is needed. However, automated systems that do not require bus operator intervention are preferable, as operators may not always remember to activate the system at the intersections equipped with signal priority equipment. Furthermore, an automated system, when coupled with two-way data communication and AVL equipment, can be set to activate signal priority only when a bus meets certain conditions for granting priority (e.g., a bus is behind schedule, on route, within a preset area, doors are closed).

A variety of technology is employed for vehicle detection and information transmission:

- Inductive loop systems were used in early TSP applications, where an inductive loop embedded in the pavement detected a transponder mounted on the underside of a bus;
- Optical emitter/detection systems (Exhibit 6-41) have been applied by many U.S. and Canadian transit systems;
- Radio frequency tags, similar to those used by the logistics industry to track packages, interact with wayside reader stations; and
- The combination of global positioning system (GPS) and wireless technology are emerging technologies for TSP application.

Exhibit 6-41
Optical TSP System Example



Source: TCQSM 2nd Edition (*5*).

Feasibility studies have concluded that there is no strong evidence that one technology works best for every situation. The AVL and APC technologies in use at a given transit agency influence the development of TSP, as does the pre-existence of traffic signal infrastructure for other priority applications (e.g., emergency vehicles). If the existing traffic signal control system's capability is not sufficient to accommodate TSP, traffic signal hardware or software updates, or both, may be needed. *TCRP Synthesis 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic* (*14*) summarizes the type of equipment used by some North American transit agencies as of 2010.

Typical Conditions for Application

There are a number of reasons to justify transit signal priority. However, signal priority should only be implemented at intersections whose traffic operations (including pedestrian and bicycle operations) are well understood.

TSP is typically applied when there is significant transit delay along a route at signalized intersections due to signal operation. Studies have found that TSP is most effective at signalized intersections operating within LOS D and E conditions with a volume-to-capacity (v/c) ratio between 0.80 and 1.00. Under LOS A through C conditions, TSP brings limited benefits as the roadway is relatively uncongested and neither major bus travel time or reliability improvements can be achieved. Under oversaturated traffic conditions (v/c greater than 1.00), long vehicle queues prevent transit vehicles from getting to the intersection soon enough to take advantage of TSP without disrupting general traffic operations (*14*). When bus volumes are high enough that TSP would be called for in the majority of signal cycles, passive signal priority or other forms of bus preferential treatment may be preferable, as the traffic signal system may not be able to grant frequent TSP requests.

Ideally, TSP is applied when the net total person delay (on transit and in general traffic) will decrease at a particular intersection or along a corridor, although policy considerations to discourage automobile travel and favor transit use may also apply. Field data collection on traffic and transit operating conditions, as well as an analysis of future conditions (often involving simulation modeling), allows for informed decisions by both transit and transportation engineering staff on the benefits and impacts of potential signal timing changes. *TCRP Report 118: BRT Practitioner's Guide* (*11*) provides a decision-making framework for implementing TSP.

Actual applications have shown that TSP achieves a greater reduction in transit travel time and variability of travel time when transit stops are located on the far side of signalized intersections, as the transit vehicle can activate the priority call, travel through the intersection and then make a stop (*14*).

TCRP Synthesis 83 (*14*) provides cost information for various TSP detection systems, along with typical per-intersection costs for implementing TSP.

Impacts on Transit Operations

The direct benefits of TSP are (*a*) travel time savings and (*b*) improved reliability, which could result in (*c*) capital and operating cost savings. The level of benefit a TSP system provides depends on a complex set of interdependent variables, including whether the signal system along the route was already optimized before TSP application (*14*).

Documented travel time savings from TSP applications in North America and Europe have ranged from 2% to 18%, depending on the length of route, traffic conditions, bus operations, and the TSP strategy deployed. Travel time savings of 8% to12% have been typical. The reduction in bus delay at signals has ranged from 15% to 80% (*14*).

TSP significantly improves schedule adherence, as measured by variability in bus travel times and arrival times at stops relative to the schedule. Bus travel time variability could be reduced by up to 35%. On high-frequency routes, TSP can also help reduce bus bunching headway variability (*14*).

Reductions in bus travel time and travel time variability can result in operating and capital cost savings, when the total time saved from running time reductions and reduced schedule recovery requirements at the ends of routes equals or exceeds the route headway, as fewer buses can then serve the route at the same headway. Even when the time savings are not enough to save a bus immediately, TSP can postpone the day that an extra bus needs to be added to the route to maintain headways, by offsetting some of the increased running time resulting from increased traffic congestion (*29*).

Exhibit 6-42 presents examples of North American TSP applications and their reported benefits.

Exhibit 6-42
Summary of TSP Benefits and Impacts

Location	Transit Mode	# of Intersections	TSP Strategies	Benefit/Impact
Portland (Tualatin Valley Hwy.)	Bus	10	Green extension, red truncation	Bus travel time reduced 1.4–6.4% Bus traffic signal delay reduced 20%
Portland (Powell Blvd.)	Bus	4	Green extension, red truncation, queue jump	Bus travel time reduced 5–8% Bus person delay generally decreased TSP impacts on traffic inconclusive
Seattle (Rainier Ave. at Genesee)	Bus	1	Green extension, red truncation	Bus signal-related stops reduced 50% Bus signal delay reduced 57% Bus travel time variability reduced 35% Average person delay reduced 13.5% Average vehicle delay did not change Side-street impacts insignificant
Toronto	Streetcar	36	Green extension, red truncation	Transit signal delay reduced 15–49% One streetcar removed from service
Chicago (Cermak Rd.)	Bus	15	Green extension, red truncation	Bus travel time reduced 7–20% Improved schedule reliability Average vehicle delay reduced 1.5 s/veh Side-street vehicle delay increased 8.2 s/veh Fewer buses required to operate service Improved passenger satisfaction
San Francisco	Light rail	16	Green extension, red truncation	Transit signal delay reduced 6–25%
Minneapolis (Louisiana Ave.)	Bus	3	Green extension, red truncation, actuated bus phase	Bus travel time reduced 0–38% Average vehicle delay increased 4.4 s/veh Skipping signal phases caused some motorist frustration
Los Angeles (Wilshire and Ventura Blvds.)	Bus	211	Green extension, red truncation, actuated bus phase	Bus travel time reduced 35% Decrease in bus delay at traffic signals

Source: ITS America (*30*).

SITE-SPECIFIC PRIORITY TREATMENTS

Queue Jumps

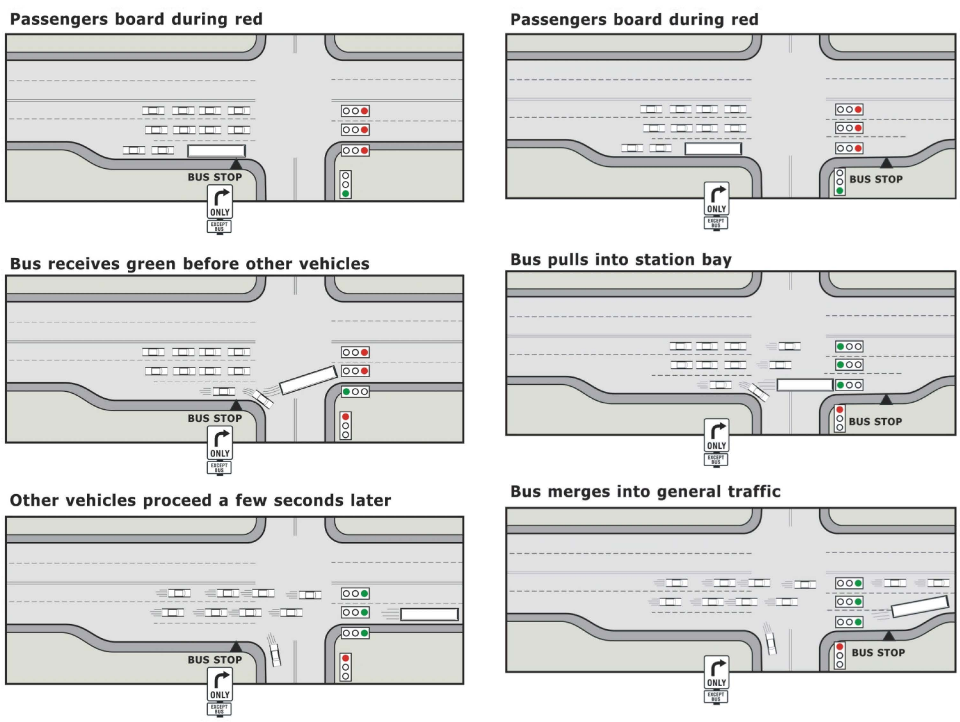
Overview

A queue jump lane is a relatively short lane that is available for buses to bypass queues of general traffic at or prior to a signalized intersection, thus reducing delay to bus passengers. Example configurations include:

- Buses enter a right- or left-turn lane (right-turn lanes being the most common) on an intersection approach and are given a green indication at the intersection in advance of general traffic;
- Buses enter an exclusive bus lane developed on the intersection approach and are given a green indication at the intersection in advance of general traffic; and
- Buses use a mid-block traffic signal (or *pre-signal*) coordinated with the downstream signalized intersection to move ahead of general traffic unimpeded.

Exhibit 6-43 illustrates the first type of queue jump lane in situations where TSP is and is not provided. Exhibit 6-44 shows photographs of the second and third types of applications.

Exhibit 6-43
Right-Turn Lane Queue Jump Process



(a) With TSP (b) Without TSP

Source: *TCRP Report 118* (*11*).

If TSP is provided, a separate, short signal phase is provided to allow the bus (and any turning vehicles in front of it) an early green indication to move into the through lane or bus loading area on the far side of the intersection, ahead of through traffic. If the bus stop is located near side, passenger alighting and boarding could occur during a red signal indication. Immediately after the bus doors close, a signal priority request would be sent to the controller to activate the special signal phase, giving an early green indication to the bus to proceed ahead of the general traffic.

If TSP is not provided, a bus could still use a right-turn lane or right-side bus lane to bypass a general traffic queue. The bus would proceed under the normal through signal phase into a far-side bus zone or bus pullout.

Exhibit 6-44
Example Queue Jump Applications with Bus Lanes

(a) Queue jump at intersection (Copenhagen)

(b) Queue jump at bus lane end (Frederiksberg, Denmark)

In both applications shown in Exhibit 6-44, a special transit signal (e.g., the vertical white bar to the right of the red indication in Exhibit 6-44[a]) is used to indicate that the bus may proceed. Such an indication has been commonly used in Canada and Europe, and has been allowed in the U.S. since the publication of the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) (*31*) for bus queue jump applications and BRT operating in semi-exclusive or mixed-use alignments. Right-turn-lane queue jump applications in the U.S., such as those illustrated in Exhibit 6-43, have typically used regular traffic signals (with appropriate signing and shielding) to control the bus queue jump movement.

Typical applications of the pre-signal shown in Exhibit 6-44[b] are at a section of reduced right-of-way width where insufficient room exists to continue a bus lane, and to allow buses to transition from a curb bus lane or bus stop to the left-turn lane at a downstream signal. In the example in Exhibit 6-44[b], the roadway width used by the bus lane is needed for a right-turn lane at the downstream intersection, while buses proceed straight through the intersection. In this case, the queue jump allows buses to merge into the through lane ahead of other traffic. The pre-signal is coordinated with the downstream intersection, so vehicles receive a green indication downstream if they have to stop at the pre-signal. These applications can also be combined with mid-block pedestrian crossings, if sufficient pedestrian demand exists and sufficient roadway length exists to queue vehicles without creating operational issues.

Typical Conditions for Application

Conditions that support the application of queue jump lanes include (*14*):

- Right-of-way availability;
- Right-turn (or left-turn) lane availability to serve as a bus bypass lane;
- Sufficient bypass lane length to allow buses to bypass the through traffic queue most of the time, particularly during peak periods;
- Low turning traffic volumes to minimize conflicts between buses and turning vehicles; and
- Availability of a far-side pullout or zone to accept buses, when used in combination with a far-side stop.

Existing utilities or other roadside features could interfere with the application of queue jump lanes.

TCRP Synthesis 83 (*14*) provides a set of questions to assist in making the decision to install queue jump lanes at intersections and provides estimates of installation costs.

Impacts on Transit Operations

Allowing a bus to bypass general traffic queuing at a signalized intersection reduces transit travel time and improves service reliability. The amount of travel time saving depends on multiple factors: (*a*) the length of the general traffic queue, (*b*) the extent the general traffic queue may block the transit vehicle from entering the queue bypass lane, (*c*) whether a free right turn is provided, and (*d*) the interference of right-turning traffic with buses in the queue jump lane.

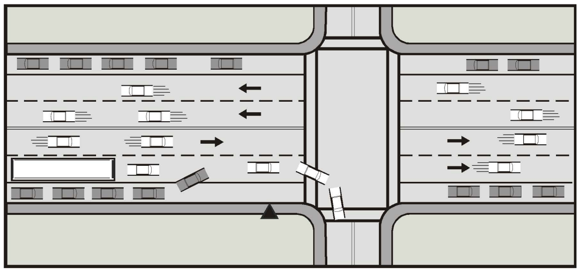
TCRP Report 118 (*11*) shows that bus queue jump lanes result in 5% to 15% reductions in travel time for buses through intersections. Such travel time reduction may also improve service reliability. The greatest reduction in bus delay at intersections resulted with queue jump lane combined with a near-side stop and TSP (*32*). A queue jump lane could cause some delay to right-turning traffic if a separate lane for buses is not provided.

Boarding Islands

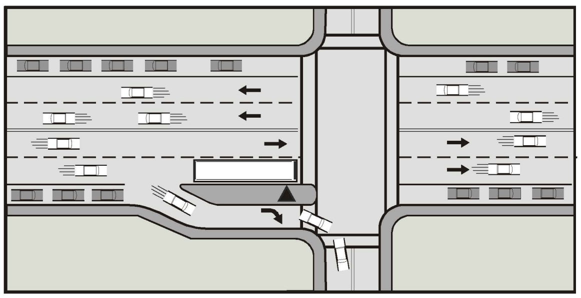
Where significant parking activity, stopped delivery vehicles, heavy right-turning traffic volumes, and other factors slow traffic in the right lane of a multiple-lane street, buses may be able to travel faster in the lane to the left. Boarding islands allow bus stops to be located between travel lanes so that buses can use a faster lane without having to merge into the right lane before every stop. Pedestrian safety issues must be addressed when considering the use of boarding islands. Exhibit 6-45 illustrates the concept of this treatment, along with two applications.

Exhibit 6-45
Boarding Island Example

Before
Traffic congestion in curb lane due to parking and turning maneuvers.



After
Bus travels in faster lane, passengers load and unload at boarding island.



(a) Concept

(b) Application (Washington, DC)

(c) Application (San Francisco)

Source: (a) City of Portland (*27*).

Curb Extensions

Overview

Curb extensions at transit stops (also known as *bus bulbs*) are similar to boarding islands in that they allow transit vehicles to pick-up passengers without moving into the curb lane. Curb extensions, typically applied with bus and streetcar operations, extend the sidewalk into the street (typically into the parking lane) so that transit vehicles do not have to pull out of the travel lane to serve passengers at the curb. This eliminates the clearance time associated with transit vehicles reentering general traffic in the through lane, thereby resulting in travel time savings. Significant travel time savings can be achieved when curb extensions are applied over a series of stops along a route.

Additional advantages of curb extensions include: (*a*) passenger waiting areas clear of the main sidewalk, (*b*) ADA-compliant landing areas for wheeled mobility aid users, (*c*) space for a shelter, and (*d*) reduced pedestrian crossing distance, if located at an intersection or mid-block crosswalk.

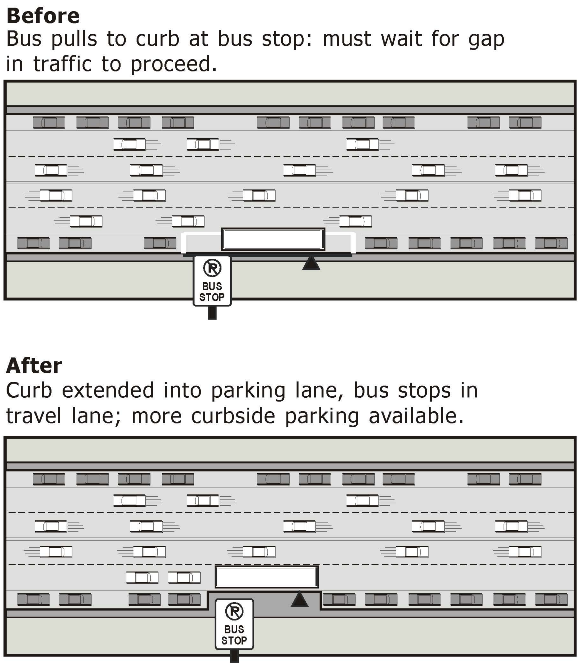
Curb extensions are typically applied on the near side of intersections or mid-block. If applied at far-side stops, the traffic queue generated behind the stopped transit vehicle should not block the intersection. Therefore, when far-side curb extensions are used, a second through lane is desirable to allow traffic to move around the stopped transit vehicle.

Even though curb extensions are typically created by extending the sidewalk into the parking lane, they can actually create more on-street parking than would exist with a stop flush with the regular curb line, as the area before or after the bus stop that would otherwise be used by buses to pull in or out of the stop can be used for additional parking.

If bicycle lanes exist, they may need to be routed around the curb extension, creating potential pedestrian/bicycle or auto/bicycle conflicts. Curb extensions can change street drainage patterns, and drainage may need to be reworked to prevent water from ponding in the stop vicinity. They may also restrict some right turns, due to the tighter curb radius associated with this treatment.

Exhibit 6-46 illustrates the use and application of curb extensions.

Exhibit 6-46 Curb Extension Examples



(a) Concept

(b) Application (Portland)

(c) Application (Vienna)

Source: (a) City of Portland (*27*).

Typical Conditions for Application

Curb extensions are typically warranted when buses experience difficulty reentering general traffic flow from stops. Conditions that support the construction of curb extensions related to bus operations include:

- Low street traffic speed,
- Low general traffic volume (fewer than 400 to 500 veh/h),
- Low right-turning traffic volume (particularly for larger vehicles such as trucks),
- High passenger volume at stop or adjacent sidewalk,
- Presence of on-street parking,
- Two travel lanes available (to allow passing of stopped buses),

- Near-side or mid-block stop location,
- Support from local business or property owners for such treatments.

Conditions that require special consideration include:

- Two-lane streets (i.e., no passing opportunity),
- Complex drainage patterns,
- High bicycle traffic along the route,
- High right-turning volume, particularly trucks, for near-side applications.

TCRP Report 65: Evaluation of Bus Bulbs (*33*) provides a set of questions to assist in making the decision to install a curb extension. *TCRP Synthesis 83* (*14*) provides a range of costs for curb extensions, which mainly depend on the cost of providing adequate drainage.

Impacts on Transit Operations

Curb extensions eliminate clearance time, the time a bus waits to reenter traffic flow in the general traffic lane. If curb extensions are implemented in a systematic manner along a route, transit travel time saving accumulates, which may produce operating cost savings. Additional benefits are a shorter pedestrian crossing distance and an increased usable sidewalk width (*14*).

TCRP Report 65(*33*) reports the results of a before-and-after study in San Francisco of the impact of curb extensions. The study found a 7% increase in bus operating speeds along the corridor, and an average11% improvement in the peak-period pedestrian flow rate (ped/min/ft) at one of the bus stops equipped with a curb extension, compared to the original sidewalk with a bus bay. *TCRP Report 65* also developed simulation models to estimate the impact of curb extensions. At near-side stops, simulated traffic speeds were higher on average with curb extensions, compared to bus pullouts, regardless of bus bay design and dwell time, when curb-lane traffic volumes were less than 1,000 veh/h. No significant difference in average simulated traffic speeds was observed with far-side stops.

Curb extensions at intersections prevent the construction of dedicated right-turn lanes. In addition, they may make right-turn maneuvers more difficult for larger vehicles due to the tighter turning radius.

SUMMARY

Exhibit 6-47 summarizes the advantages and disadvantages of the bus preferential treatments presented in this section.

Exhibit 6-47
Bus Preferential Treatments Comparison

Treatment	Advantages	Disadvantages
Exclusive Bus Lanes	• Increases bus speed by reducing sources of delay • Improves reliability • Increases transit visibility	• Traffic/parking effects of eliminating an existing travel or parking lane must be carefully considered • Requires ongoing enforcement
Signal Priority	• Reduces traffic signal delay • Improves reliability	• Risks interrupting coordinated traffic signal operation • Risks lowering intersection LOS, if intersection is close to capacity • Requires interjurisdiction coordination • Cross-street buses may experience more delay than time saved by the favored routes
Queue Bypass	• Reduces delay from queues at ramp meters or other locations	• Bus lane must be available and longer than the back of queue
Queue Jump	• Reduces delay from queues at signals • Buses can leap-frog stopped traffic	• Right lane must be available and longer than the back of queue • Special transit signal required • Reduces green time available to other traffic • Bus drivers must be alert for the short period of priority green time
Curb Extensions	• Eliminates reentry delay • Riding comfort increased when buses don't pull in and out of stops • Increases on-street parking by eliminating need for taper associated with bus pullouts • More room for bus stop amenities • Reduces pedestrian crossing distance	• Requires at least two travel lanes in bus's direction of travel to avoid blocking traffic while passengers board and alight • Bicycle lanes require special consideration
Boarding Islands	• Increases bus speed by allowing buses to use faster-moving left lane	• Requires at least two travel lanes in bus's direction of travel and a significant speed difference between the two lanes • Uses more right-of-way than other measures • Pedestrian/ADA accessibility, comfort, and safety issues must be carefully considered

Sources: City of Portland (*27*) and TCQSM, 1st Edition (*34*).

4. OPERATIONAL TOOLS

OVERVIEW

The previous section focused on infrastructure treatments to improve bus speed and reliability. Those kinds of improvements typically cannot be directly implemented by a transit agency and require coordination with and permission from other agencies, typically those responsible for operating and maintaining the roadways used by buses.

This section focuses on operational treatments over which transit agencies typically have more direct influence. There are a number of options available in the way that bus service is designed and operated that can also provide significant capacity, speed, and reliability benefits.

BUS STOP PLACEMENT

The number and location of bus stops along a route can directly influence bus travel time and reliability and can also influence the effectiveness of transit preferential treatments.

Bus Stop Relocation

The traffic signal systems used on arterial streets are often designed to progress the flow of automobile traffic: the signals at a series of intersections are timed to turn green as a platoon of vehicles approaches each intersection from the preceding intersection. However, signal progression for general traffic may work against buses, as buses will often arrive at the intersection while the signal is green, but by the time passengers using the stop have been served, the signal will have turned red. In this case, the bus will need to wait for the signal to turn green (if the stop is located near side) or the bus will likely arrive at the next signal on red (if the stop is located far side). Ideally, a bus would be able to serve passengers on red while also being able to take advantage of the green as soon as possible (upon arrival at the intersection, or after passenger movement was completed).

It may be possible to relocate bus stops so that buses can take better advantage of the existing signal progression. The combination of archived AVL and APC data can be used to identify signalized intersections where buses must wait for extended periods of time before or after serving passengers. These locations are candidates for moving bus stops from one side of the intersection to the other.

It should be kept in mind that signal timing patterns usually change over the course of the day (for example, favoring the peak traffic direction), so that a bus stop relocation that might be effective during the morning peak might be counter-productive during the afternoon peak. The potential impact of relocations should be evaluated for peak and off-peak periods prior to implementation. It is desirable to coordinate with the agency operating the traffic signals, to make them aware that the bus stop spacing has been optimized for the existing signal timing so they can preserve the bus benefits when they retime their signals. The factors listed previously in Exhibit 6-9 (page 6-13), such as pedestrian access issues and transfer opportunities, should also be considered before relocating stops.

Bus stop relocation can also be a useful technique for reducing the impact of other vehicles on bus operations. For example, when a bus stop is located in an exclusive right-turn lane, queues of turning vehicles may inhibit bus access to the stop. Locations such as this are also candidates for bus stop relocation, and can be identified by talking with bus drivers about problem locations, and through analyzing archived AVL data.

Bus Stop Consolidation

In general, minimizing the number of stops that buses must make will improve overall bus speeds, as buses are able to take better advantage of the signal progression provided to general traffic and will also spend more time in motion instead of being delayed (e.g., decelerating, accelerating, waiting for a traffic signal to turn green, waiting to pull back into traffic) with each additional stop. Furthermore, the more consistently that buses stop at each stop along the route, the more consistent headways between buses will be, because buses will tend to travel in the same pattern along their route from one trip to the next.

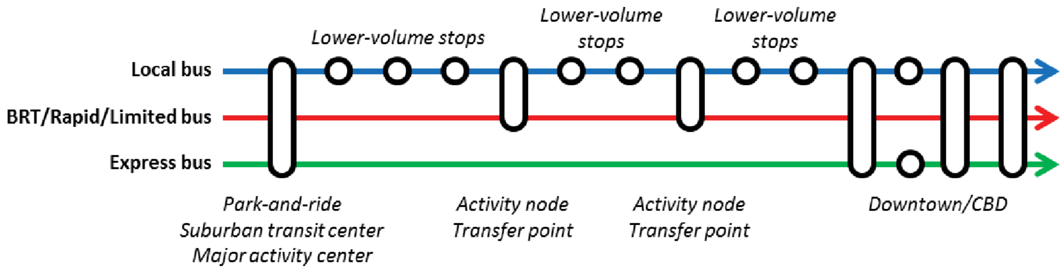
Consolidating bus stops involves trade-offs between the convenience of the passengers using a particular stop, and those passengers already aboard a bus who are delayed each time the bus stops. Requiring passengers—particularly those with mobility difficulties—to walk a long distance to another stop may discourage them from continuing to use transit and may require ADA-eligible passengers to be served with more expensive demand-responsive service. Eliminating a stop can be politically difficult at times when local residents object to having “their” stop removed. Finally, even when the distance to the next bus stop is short, poor or missing pedestrian facilities along the street with bus service may prevent walking access to it.

However, when stops are located close together (e.g., every block), and a consistent, objective process is used to determine which stops are eliminated, consolidating bus stops can provide benefits to all transit users. In these cases, the time spent by individual passengers to walk an extra block to a bus stop will typically be more than recouped by time saved on board the bus because of the improved bus running speed. At the same time, care must be taken that dwell times at critical stops (those stops with the highest dwell time) are not lengthened when a nearby stop is removed and passenger demand is shifted to the critical stop.

Limited-stop and express services as alternatives to consolidating stops in high-ridership corridors.

In high passenger-volume corridors, an alternative to eliminating stops is providing peak-period or all-day *limited-stop* (bypassing minor stops) or *express* (operating non-stop over a significant portion of the route) service in conjunction with local service that serves all stops. Passengers traveling long distances can do so more quickly, and it is easier to convey information to passengers about which stops are made when there are fewer stops. Passengers can transfer between services at shared stops or can choose to walk a little farther to get to their destination rather than wait for a local bus. Implementing limited-stop service can be a first step in the development of a bus rapid transit line. Exhibit 6-48 illustrates the relationship between local, limited and BRT, and express bus stop spacing patterns in a transit corridor. Although this exhibit shows different service types sharing selected stops, it is also possible to provide services with separate stops in the same general vicinity for operational or service branding reasons. The exhibit also shows that stop spacing will typically be farther apart in the suburbs and closer together in higher-density areas, reflective of each area’s relative ridership demand.

Exhibit 6-48
Bus Stop Spacing Patterns Illustrated



Impacts on Transit Operations

Several studies report on the travel time savings due to stop consolidation:

- TriMet reported a 5.7% reduction in bus running time attributable to an increase in average spacing of 6% for inbound and 8% for outbound stops (*35*).
- MUNI reported an average bus speed increase of 4.4% to 14.6% when average stop spacing was reduced from 5.9 to 2.5 stops per mile (*7*).
- Los Angeles' first two BRT lines, along the Wilshire–Whittier and Ventura Boulevard corridors, implemented limited-stop service on top of the existing local bus service. These lines provided a 23 to 29% reduction in average running time, two-thirds of which was attributable to the bus stop consolidation (*36*).

Cumulative Impact of Bus Stop Placement with other Preferential Treatments

Moving an intersection from near side to far side, or vice versa, may allow another preferential treatment to be applied or its performance improved. For example, TSP's effectiveness is greatest when bus stops are located on the far side of signalized intersections. On the other hand, queue jumps can be triggered after passenger movement has been completed at a near-side stop (*14*).

BUS STOPPING PATTERNS

These tools organize buses into groups that can make more efficient use of the bus facility.

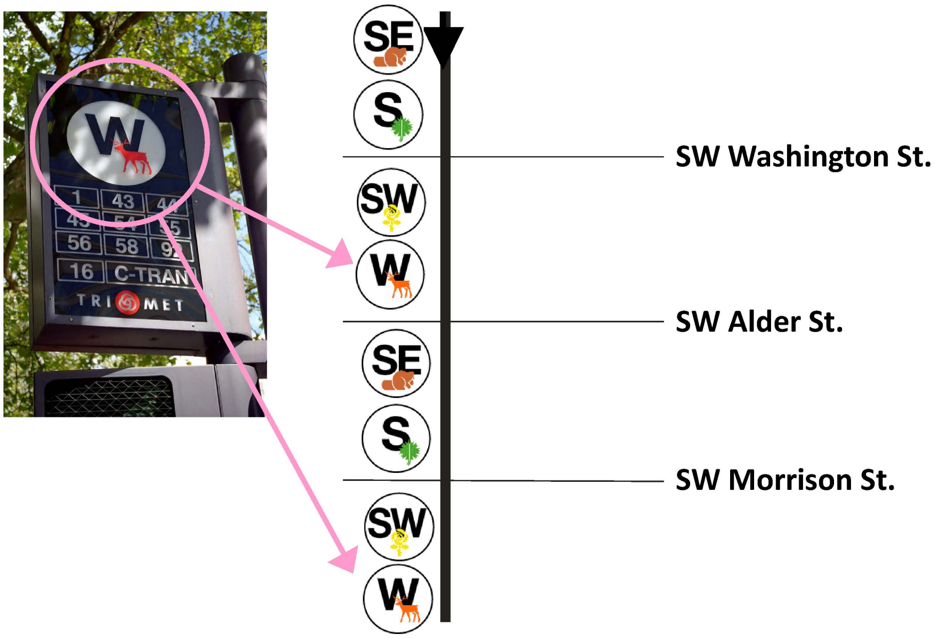
Skip-Stop Operation

When all buses using a particular street stop at every bus stop, the available capacity is used up more quickly than if buses are spread out among several groups of stops. This technique of spreading out stops among two to four alternating patterns, known as *skip-stop operation,* offers the ability to substantially improve bus speeds and overall facility bus capacity. It works well when bus volumes are heavy and bus stops are initially closely spaced.

TriMet has used skip stops for many years along its 5th and 6th Avenue transit mall in Portland. Exhibit 6-49 shows the pattern used immediately prior to the addition of light rail service to the mall. Bus routes were divided into groups based on their geographic destination. These groups were communicated to passengers via a prominently displayed compass direction (e.g., S, SE) on the bus stop signs, placed alongside color icons (e.g., orange deer, brown beaver) that were included for continuity with an older system of symbolizing the groups. Each group consisted of multiple routes—for example, 10 TriMet routes plus routes operated by C-Tran were included in the “W” or “West” group illustrated in Exhibit 6-49.

Each block face along the transit mall contained two bus stops, and each group stopped every other block, resulting in four groups in the skip-stop stopping pattern. By spreading buses over four stops, the transit mall was able to accommodate up to 175 buses per hour at its peak (*21*), a total that would be impossible to achieve if all the buses shared the same stops. During construction of light rail tracks on the transit mall, TriMet switched to a basic lettering system to indicate stopping groups (e.g., W-X-Y-Z) on the streets used as the temporary transit mall, and retained this system once buses were reintroduced to the transit mall. Denver uses a similar lettering system to indicate skip-stop groups along the downtown portions of 15th and 17th Streets, which is illustrated in *TCRP Synthesis 83* (*14*).

Exhibit 6-49
Example Skip-Stop Pattern and Signing



Skip stops can greatly increase bus facility capacity and average speeds, at the potential expense of added complexity to passengers.

Skip-stopping operations allow a street’s bus capacity to nearly equal the sums of the capacities of the individual stops, thereby providing a nearly three- or four-fold increase in capacity, as well as substantially improving average travel speeds. Due to traffic control delays, irregularity of bus arrivals, and other factors, the actual capacity increase will be somewhat less than the theoretical maximum. To maximize these capacity and speed benefits, buses must be able to use the adjacent lane to pass other buses. When the adjacent lane operates at or close to its capacity, buses may not be able to pass other buses easily and the improvement provided by skip-stop operations will be lower.

Platooning

Platooning occurs when a set of buses moves along a street as a group, much like individual cars in a train. Passing activity is minimized, resulting in higher overall travel speeds, and bus stop loading areas are used more efficiently, resulting in a higher capacity. Platoons can be deliberately formed, through careful scheduling and field supervision; this can be difficult and is a rare practice in North America. More commonly, platoons can be developed by traffic signals, when several buses use the facility at the same time, much as platoons of vehicles form and move down the street together after having been stopped at a traffic signal.

In downtown Ottawa, the city's busways feed into arterial street bus lanes. These lanes have accommodated the scheduled volumes of buses in part because the traffic signal progression on those streets is designed to favor buses (i.e., both bus travel time between stops and dwell times at stops are taken into consideration). The combination of the exclusive lanes and the signal progression naturally forms bus platoons, even though buses might not arrive downtown exactly at their scheduled time (*37*).

ROUTE DESIGN

Movement Restriction Exemptions

The most direct route for buses may not be possible because of left-turn restrictions at intersections. These restrictions are often implemented when there is insufficient room to develop left-turn lanes or when traffic volumes preclude good intersection operation when traffic signal cycle time is taken away for left-turning traffic. When left-turn restrictions are a result of traffic congestion, rather than safety, it may be feasible to exempt buses from the restriction without unduly impacting intersection operations, as illustrated in Exhibit 6-50(a), particularly when bus arrivals are relatively infrequent.

Traffic calming measures designed to keep through traffic out of neighborhoods, such as traffic diverters that force vehicles to turn at an intersection may create issues for community bus routes that penetrate neighborhoods instead of operating on the major streets. In these cases, providing a bus exemption to the turn restrictions allows buses to continue straight when other vehicles must turn.

In some cases, signing alone is insufficient to prevent cut-through traffic on a street and physical barriers are used to sever the street connection, with the side effect of preventing bus travel along the route. In other cases, development patterns have resulted in no street connection between adjacent land uses that could otherwise be served by a bus route, and local residents may not desire a new connection that could generate cut-through traffic in their neighborhood. To address both of these issues, some European cities have developed *bus gates* that allow bus traffic through a roadway connection (along with pedestrians, bicyclists, and emergency vehicles), but not general traffic. The retractable bollard system shown in Exhibit 6-50(b) would not be MUTCD-compliant, but an alternative system employing gates (such as those used to control access to and from parking lots) could be compliant.

(a) Left-turn exemption (Portland)

(b) Bus gate (Copenhagen)

Exhibit 6-50 Examples of Bus Exemptions from Movement Restrictions

Parking Restrictions

Parking restrictions can be used to implement several of the bus preferential treatments described in Section 3. Parking restrictions are typically required in the vicinity of a curbside stop to allow buses to pull out of the street and up to the curb to load and unload passengers. In areas where high parking turnover interferes with the flow of traffic on a street, parking restrictions may allow restriping to provide a right-turn-only lane that can also be used by buses as a queue jump lane. Part-time parking restrictions can be used to provide part-time exclusive bus lanes. Whenever parking restrictions are being considered, the impacts to general traffic and adjacent land uses from the loss of on-street parking must also be considered. In some instances, parking restrictions are mitigated through stop consolidation, which can increase the overall number of parking spaces in an area.

Design Standards

Developing objective design standards that specify minimum and maximum bus stop spacing, criteria for diverting a route to serve a particular trip generator, and so on can make it easier for transit agencies to improve or at least maintain transit service quality. Having, and consistently applying, these standards can help overcome objections to individual changes and can make larger-scale changes more politically acceptable. For example, having bus stop spacing standards can make it easier to improve service at a later date by justifying the benefits provided by longer stop spacing. Service diversion standards based on person-delay can make a case for or against changes in routing, depending on the net impact on passengers that would result.

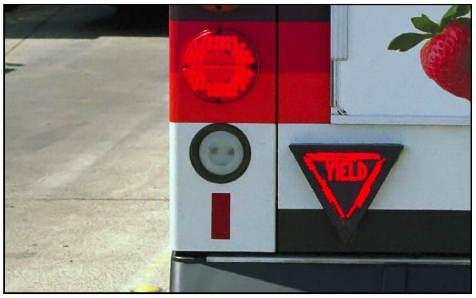
YIELD-TO-BUS LAWS

Some jurisdictions, including the states of Florida, New Jersey, Oregon, and Washington, and the provinces of British Columbia and Québec, have passed laws requiring motorists to yield to buses signaling to reenter the street from a bus stop. Depending on motorist compliance with the law, the delay associated with a bus merging back into traffic from a curbside stop can be almost eliminated. Some agencies also view these laws as a way to improve safety for buses and other vehicles. *TCRP Synthesis 49* (*8*) addresses the effectiveness of these laws.

Some jurisdictions (e.g., Québec and Washington) remind motorists of the law through the use of stickers mounted to the back of the bus. Some agencies in areas without yield-to-bus laws also use similar stickers appealing to motorist courtesy to let the bus back in. Oregon has developed a flashing electronic YIELD sign that has traffic control device status (i.e., motorists must obey it like they would a traffic signal or regulatory sign). Examples of these approaches are shown in Exhibit 6-51.

Exhibit 6-51
Yield-to-Bus Law Notification Examples

(a) Montréal



(b) Portland

SUMMARY

Exhibit 6-52 summarizes the advantages and disadvantages of the operational tools presented in this section.

Exhibit 6-52
Bus Operations Tool Comparison

Treatment	Advantages	Disadvantages
Parking restrictions	• Increases bus speeds • Increases overall street capacity and reduces traffic delays	• May significantly impact adjacent land uses (both business and residential) • Requires ongoing enforcement
Movement restriction exemption	• Reduces travel time by eliminating detours to avoid movement restrictions	• Potentially lowers intersection level of service • Safety issues with turn restrictions must be carefully considered • Potential neighborhood opposition to new street connections, even if bus-only
Bus stop relocation	• Uses existing signal progression to bus's advantage	• May increase walking distance for passengers transferring to a cross-street bus
Bus stop consolidation	• Reduces number of stops, thereby improving average bus speeds	• Increases walking distances for some riders • Pedestrian environment may not support walking to the next closest stop
Skip-stop stopping patterns	• Substantially improves bus speed and capacity	• Unfamiliar riders may be unsure about where to board their bus • Requires available adjacent lane
Platooning	• Reduces bus passing activity	• May be difficult to implement
Design standards	• Service changes to improve operations more easily justified • Supports consistent transit planning and design	• Too rigid an application of standards can be just as bad as not having standards

Sources: City of Portland (*27*) and TCQSM 1st Edition (*34*).

5. BUS CAPACITY METHODOLOGY

INTRODUCTION

This section presents a computational methodology for determining the bus and person capacity of loading areas, stops, and facilities. As discussed in Chapters 2 and 3, bus service can be operated with a variety of service types (e.g., local bus, commuter bus, BRT) and stopping patterns (e.g., all stop, limited stop, express) in a variety of operating environments (e.g., mixed traffic, semi-exclusive, exclusive, grade separated), resulting in dozens of possible combinations of service. Nevertheless, the basic process for determining bus capacity, shown in Exhibit 6-53, is the same for all-stop local bus service in mixed traffic, express BRT service on a grade-separated busway, and every combination in between.

This section's methodology is derived in large part from the research originally presented in *TCRP Report 26: Operational Analysis of Bus Lanes on Arterials* (*21*). Additional contributions to the methodology are referenced in the text at the appropriate points.

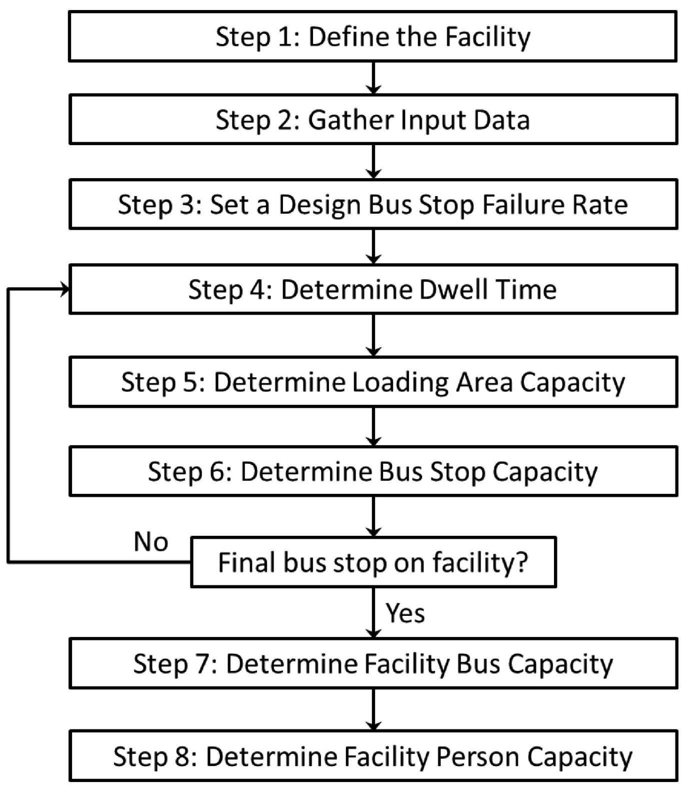


Exhibit 6-53
Bus Capacity Methodology Flowchart

STEP 1: DEFINE THE FACILITY

As introduced earlier in the chapter (Exhibit 6-11, page 6-15), bus capacity is calculated for three key locations:

1. *Bus loading areas (berths),* curbside spaces where a single bus can stop to load and unload passengers;
2. *Bus stops,* consisting of one or more adjacent loading areas; and
3. *Bus facilities,* continuous sections of roadways used by buses that include at least one stop, but typically many more.

For the purposes of conducting a capacity analysis, a facility can be defined very flexibly. It can be a discrete piece of infrastructure (e.g., a median busway), a defined section of roadway (e.g., the portion of a downtown street between two defined cross-streets), or the streets followed by a particular route (e.g., a BRT route). As a result, a facility can include a mix of operating environments (e.g., a mix of bus lanes and mixed-traffic operations) and physical roadways (e.g., a turn from one street to another), and can be used by multiple bus routes using a variety of stopping patterns. However, when two different types of roadways used by buses are located side by side within the same right-of-way (e.g., a median busway used by a BRT route, with local bus service in the adjacent general traffic lanes), these should be treated as two separate facilities.

Importantly, all bus stops located along the defined length of the facility need to be included in the analysis, as individual bus stop characteristics are inputs to the bus speed methodology presented in Section 6. In addition, bus operations issues can occur at any stop, not just the busiest stop, so it is necessary to evaluate each stop along the facility for potential problems.

STEP 2: GATHER INPUT DATA

Bus Stop Demand Data

The following demand data associated with individual bus stops are required to conduct a capacity analysis. All data are for a defined hour (typically a peak hour).

- *Average (mean) dwell time.* As discussed in Step 4, this input can be field measured (preferred for existing conditions); estimated based on passenger volumes, fare collection method, vehicle design, and passenger loads; or estimated based on default values.
- *Dwell time variability,* measured by the coefficient of variation of dwell times (the standard deviation of dwell times divided by the average dwell time). As discussed in Step 3, this input can be field measured or estimated based on default values.
- *Failure rate,* defined as the percentage of buses that arrive at the bus stop to find all available loading areas already occupied. As discussed in Step 3, this input can be field measured, but is more typically applied as a design value to develop a design capacity that reflects a desired level of operational reliability.
- *Passenger demand peak-hour factor (PHF),* defined as the hourly passenger demand at a bus stop (sum of boarding and alighting passengers), divided by four times the passenger demand during the peak 15 min of the hour. This input can be field measured or assigned a default value.

Bus Stop Location Data

- *Position relative to the roadway.* As was illustrated in Exhibit 6-5 (page 6-9), bus stops can be *on-line* (the bus stops in the travel lane) or *off-line* (the bus pulls out of the travel lane to serve a stop).
- *Position relative to an intersection.* As was illustrated in Exhibit 6-8 (page 6-12), bus stops can be *near side* (located immediately prior to an intersection), *far side* (located immediately after an intersection), or *mid-block* (located away from the influence of an intersection).
- *Bus stop design type.* As was illustrated in Exhibit 6-12 (page 6-16), several different bus stop designs are possible. The bus stop design needs to be characterized as *linear* or *non-linear.*
- *Number of loading areas.*
- *Bus facility type,* reflecting the ability of buses to move around other vehicles in their lane. As illustrated in Exhibit 6-54, Type 1 bus lanes do not allow buses to leave their lane. Type 2 bus lanes allow buses to move into the adjacent lane, traffic permitting, to move around other vehicles using the lane. Type 3 bus lanes provide two lanes for the exclusive use of buses.
- *Traffic signal timing,* measured by the ratio of the average green time available for bus movement divided by the traffic signal cycle length, or g/C ratio. If transit signal priority is provided, the amount of extra green time potentially provided should be included, as discussed in more detail in Step 6.
- *Curb lane traffic volume,* in vehicles per hour.
- *Right-turning traffic volume and capacity,* in vehicles per hour.
- *Parallel pedestrian crossing volume* conflicting with right-turning traffic, in pedestrians per hour.

Skip-Stop Data

When a skip-stop stopping pattern is used (see Section 4 for a definition and examples), the following additional data are required:

- *Number of stops in the stopping pattern.*
- *Bus arrival pattern* (random, typical, platooned). In a random arrival pattern (typically caused by poor scheduling, poor schedule adherence, or the influence of a nearby timed transfer location), buses arrive in clumps, with large gaps between bus arrivals and significant amounts of passing activity occurring. In a platooned arrival pattern, bus arrivals are spread out and buses tend to travel along the facility as a unit, like cars of a train, with minimal passing activity. In a typical arrival pattern, bus arrivals are scheduled to be spread out, but some passing activity occurs due to imperfect schedule adherence.
- *Traffic volume and capacity of the adjacent lane (i.e., lane to the left of the curb lane),* in vehicles per hour. If there is no adjacent lane, the volume-to-capacity (v/c) ratio of the adjacent lane is set to 1.0.

Exhibit 6-54
Bus Lane Types

Type 1

Buses have no use of adjacent lane

- Channelized bus lanes (a, b)
- Contraflow bus lanes (b, c)
- Busway stations without passing lanes (c)
- Mixed-traffic operations with only one travel lane (d)

(a) Denver, (b) Orlando, (c) Eugene, (d) Portland

Type 2

Buses may move into adjacent lane, traffic permitting

- Part-time exclusive bus lanes (e)
- Full-time exclusive bus lanes with passing opportunities (f)
- Mixed-traffic operations with two or more lanes (g, h)

(e) Montréal, (f) Madison, (g) Portland, (h) Milwaukee

Type 3

Buses have full use of adjacent lane

- Dual bus lanes (i)
- Busway stations with passing lanes (j)

(i) New York, (j) Miami

STEP 3: SET A DESIGN BUS STOP FAILURE RATE

Bus loading area capacity is maximized when a bus is available to move into a loading area as soon as the previous bus vacates it. However, this condition is undesirable for several reasons: (*a*) bus travel speeds are reduced, due to the time spent waiting for a loading area to become available; (*b*) bus schedule reliability suffers because of the additional delays; and (*c*) buses block traffic in the street while waiting to enter the bus stop. The more often that bus stop failure occurs, the higher the bus throughput over the course of the hour, but the more severe the operational problems.

Consequently, bus capacity analysis incorporates the concept of a *failure rate* that sets how often a bus should arrive at a stop only to find all loading areas occupied. The selection of a design failure rate sets the bus stop's *design capacity*—the number of buses that can be served in an hour at a desired level of operational reliability. The design failure rate should balance capacity and operational needs. Suggested values are as follows:

- In downtown areas, design failure rates between 7.5 and15% are recommended, reflecting a tradeoff between maintaining bus travel speeds and achieving the higher capacities required in downtown areas. At a 15% failure rate, queues form behind the bus stop for about 10 minute out of the hour, and simulation indicates that bus speeds at capacity are about 20% lower than when scheduled bus volumes are well below capacity (*21*).
- Outside downtown areas , a design failure rate of 2.5% is recommended whenever possible, particularly when off-line stops are provided, as queues will block a travel lane whenever a bus stop failure occurs. However, failure rates up to 7.5% can be accepted (*21*).

Although the failure rate is typically set as a design value, it can also be measured in the field when evaluating bus capacity under existing conditions.

Design capacity is effectively maximized at a 25% failure rate; lower failure rates are recommended for more reliable and higher-speed operation.

Design capacity is effectively maximized at a failure rate of 25% and the capacity achieved with a 25% design failure rate is termed *maximum capacity*. Mathematically, throughput would be highest if a constant queue of buses existed to move into a bus stop (a 100% failure rate); however, the resulting low bus speeds and poor traffic operations would likely be considered unacceptable. Moreover, even with a constant queue of buses, not all of the loading areas could be utilized simultaneously unless each bus's dwell times were tightly managed, allowing a set of buses to enter and exit the stop simultaneously (known as *platooning*), something difficult to achieve consistently in practice. Without platooning, some buses would dwell longer than others and block access to empty loading areas in front of them.

Operating margin.

The failure rate is used in combination with dwell time variability and the average dwell time (both discussed in Step 4) to provide an *operating margin*, the maximum amount of time that an individual bus dwell time can exceed the average dwell time without creating the likelihood of a bus stop failure, when the number of buses scheduled to use the stop approaches the stop's capacity. The lower the design failure rate, the greater the operating margin and schedule reliability, and the lower the loading area capacity. Conversely, the greater the design failure rate, the lower the operating margin and schedule reliability, but the greater the loading area capacity.

Standard normal variable Z.

If a series of dwell time observations were to be plotted, they would form a normal distribution similar to the one shown in Exhibit 6-55(a). A narrower distribution with a higher peak would indicate less variability, while a wider distribution with a lower peak would indicate greater variability. From statistics, the area under and to the right of a given point Z on a normal distribution curve (e.g., the shaded area in Exhibit 6-55[a]) represents the probability that any given bus's dwell time will be longer than that amount. The standard normal distribution can also be plotted as a cumulative probability curve as shown in Exhibit 6-55(b). For example, if the desired failure rate is 10% (i.e., a 90% probability that any given dwell time will not cause interference with the following bus), the corresponding Z value is 1.28.

The dwell time value t_i corresponding to Z is incorporated in Equation 6-2:

Equation 6-2

$$Z = \frac{t_{om}}{s} = \frac{t_i - t_d}{s}$$

where

Z = standard normal variable corresponding to a desired failure rate,

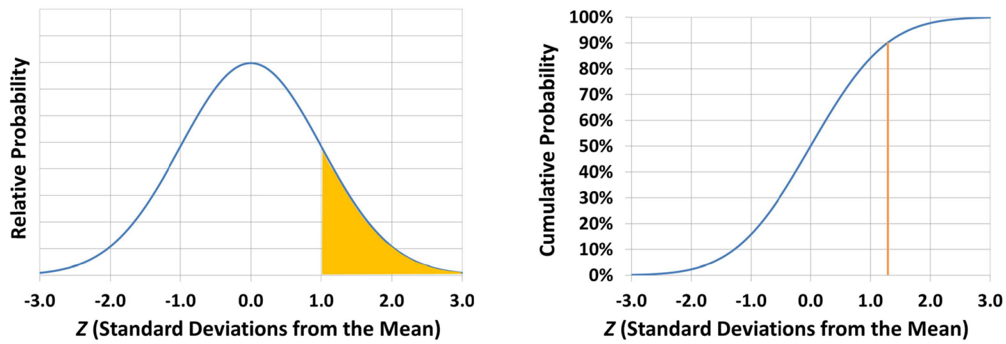
s = standard deviation of dwell times,

t_{om} = operating margin (s),

t_d = average dwell time (s), and

t_i = dwell time value that will not be exceeded more often than the desired failure rate (s).

Exhibit 6-55
Statistical Basis of Failure Rate



(a) Standard normal distribution

(b) Probability of bus stop failure associated with *Z*

Rearranging Equation 6-2 provides the operating margin required to achieve a particular design failure rate, when a bus stop operates close to its capacity:

Equation 6-3

$$t_{om} = sZ = c_v t_d Z$$

where c_v is the coefficient of variation of dwell times and all other variables are as previously defined.

Exhibit 6-56 provides values of Z corresponding to different design failure rates.

Exhibit 6-56
Values of *Z* Associated with Given Failure Rates

Design Failure Rate	*Z*
1.0%	2.330
2.5%	1.960
5.0%	1.645
7.5%	1.440
10.0%	1.280
15.0%	1.040
20.0%	0.840
25.0%	0.675

Source: *TCRP Report 26* (*21*).

Exhibit 6-57 illustrates the relationships between failure rate, operating margin, and loading area bus capacity. For the conditions shown in the exhibit (60-s dwell time and 60% dwell time variability), a 1% failure rate results in a design capacity approximately half of the loading area's maximum capacity (achieved at a 25% failure rate). Achieving this failure rate requires an operating margin of more than 80 s, meaning that dwell times would normally have to exceed 140 s (60-s average dwell time plus 80-s operating margin) before a queue would develop (assuming that bus arrivals at the stop are spread out over the hour, rather than scheduled to occur at the same times).

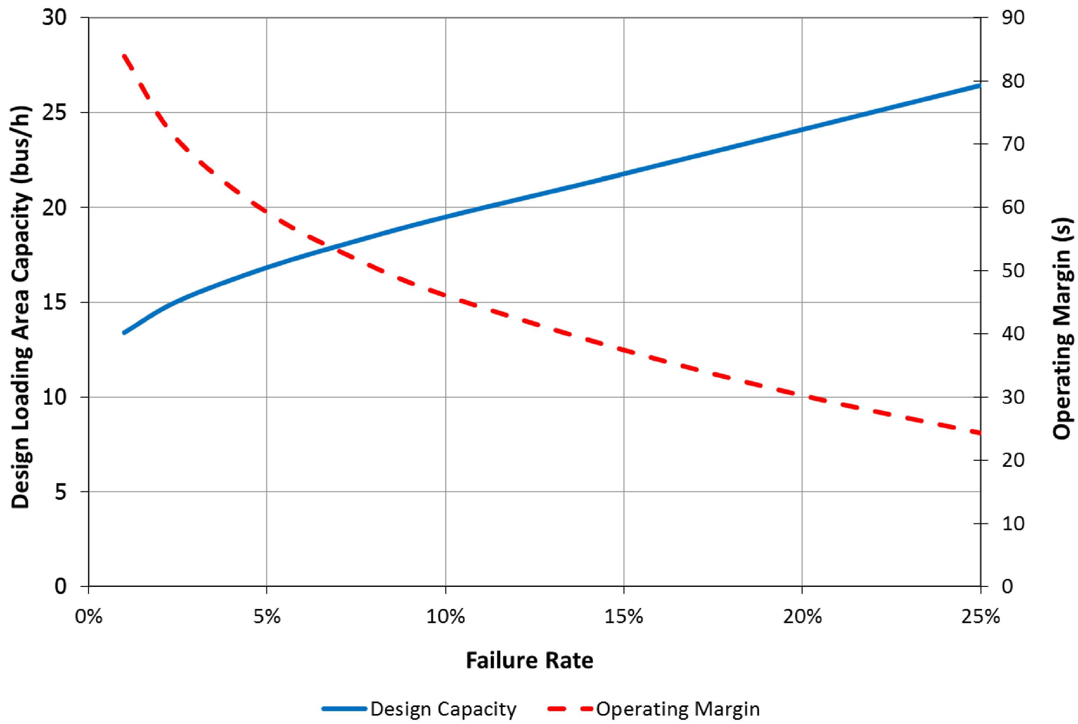


Exhibit 6-57
Illustrative Relationships Between Failure Rate, Operating Margin, and Design Loading Area Bus Capacity

Note: Assumes 60-s average dwell time and 0.6 coefficient of variation of dwell times.

STEP 4: DETERMINE DWELL TIME

Estimating Dwell Time

Three methods can be used to estimate bus dwell times:

1. *Field measurements*—best for evaluating an existing bus route,
2. *Default values*—suitable for future planning when reliable estimates of future passenger boarding and alighting volumes are unavailable, and
3. *Calculation*—suitable for estimating dwell times when passenger boarding and alighting counts or estimates are available.

Method 1: Field Measurements

The most accurate way to determine bus dwell times at a stop is to measure them directly. An average (mean) dwell time and its standard deviation can be determined from a series of observations. Appendix B presents a standardized methodology for measuring bus dwell times in the field.

Best for evaluating existing bus routes. See Appendix B for details.

Archived AVL data can be a valuable source of dwell time, but may require cleaning before use in a capacity analysis. See Appendix C for details.

Archived AVL data can also be used to determine average dwell time and its standard deviation. However, analysts using this method must be aware of the method used by the AVL system to determine dwell time. Many AVL systems are set to record door opening and closing time, which may include time spent not serving passenger movements (e.g., waiting until a traffic signal turns green), whereas the TCQSM defines dwell time solely as the sum of door opening and closing time and passenger service time. Not accounting for time with the doors open, but no passenger movement occurring, can result in overestimated dwell times. Some Dutch transit systems use door sensors to distinguish passenger service time from other time spent waiting at a stop (*38*). *TCRP Report 113* (*38*) provides guidance on setting up and using AVL data to determine dwell times.

Method 2: Default Values

Suitable for future planning when reliable passenger estimates are unavailable.

If field data or passenger counts are unavailable for a bus stop, the following representative values can be used to estimate dwell time: 60 s at a downtown stop, transit center, major on-line transfer point, or major park-and-ride stop; 30 s at a major outlying stop; and 15 s at a typical outlying stop.

Method 3: Calculation

Suitable when passenger counts or estimates are available, or when comparing different fare payment options.

This method requires that hourly passenger counts or estimates be available for the stop, categorized by the number of boarding and alighting passengers and—possibly—by fare collection. This method is also useful for estimating changes in dwell time that could result from changes in the fare collection method.

1. *Determine the average passenger boarding and alighting volumes per bus.* Divide the number of hourly boarding passengers by the number of buses serving the stop during the hour. Repeat the calculation using the number of hourly alighting passengers.

2. *Determine the mix of fare payment methods.* This value can be estimated from (*a*) farebox data specific to the stop, if available, (*b*) a planned fare collection method (e.g., planned proof-of-payment for a BRT route, planned switch to a new fare-collection technology), or (*c*) defaulted from system-level fare payment data.

3. *Assign boarding volumes by bus door channel.* There are a number of possible scenarios; the most common are:

- *Single-channel boarding, all fares paid or inspected upon boarding.* Assign all boarding volume to the front door.
- *Double-channel boarding, all fares paid or inspected upon boarding.* Split the boarding volume into (*a*) those who need to interact with a farebox and (*b*) those who just need a visual inspection of their fare media (e.g., flash pass, paper transfer, mobile phone). Assign smart card users, if any, to the channel(s) equipped with smart card terminals.
- *All-door boarding, free or pre-paid fares.* Use Exhibit 6-58 to determine the boarding volume through the busiest door channel.

Exhibit 6-58
Percent Passengers Using Busiest Bus Door Channel (No Fare Payment)

Available Door Channels	Percent Passengers Through the Busiest Door Channel	
	Boarding	Alighting
2	60%	75%
3	45%	45%
4	35%	35%
6	25%	25%

Source: Derived from Exhibit 4-3 in TCQSM, 2nd Edition (*5*).
Note: It can be assumed that boarding passengers are evenly divided among the remaining door channels. With 2 doors available, assume 25% of alightings through the front door and 75% through the rear door. When the front door has 2 door channels, assume that alighting passengers only use the non-farebox door channel. Assume that the remaining alighting passengers are evenly divided among the remaining door channels.

4. *Assign alighting volumes by bus door channel and adjust boarding volumes if necessary.* Again, there are a number of possible scenarios; the most common are:

- *Single-channel boarding, all fares paid or inspected upon boarding.* In the absence of local information, it can be assumed that 25% of alightings occur through the front door and that the remainder occur via the rear door(s).
- *Double-channel boarding, all fares paid or inspected upon boarding.* In the absence of local information, it can be assumed that 25% of alightings occur through the non-farebox front door channel and that the remainder occur via the rear door(s). Boarding occurs simultaneously through the other front door channel and can use both front door channels once the alighting movement has ended.
- *All-door boarding, free or pre-paid fares.* Use Exhibit 6-58 to determine the alighting volume through the busiest door channel. The busiest alighting door channel may not be the same as the busiest boarding door channel; however, assuming that they are the same produces a conservative result.
- *Pay-on-exit.* Assign all alighting volume to the front door and assume only a single passenger can alight at a time, even if two door channels are available, unless (*a*) the bus interior provides enough circulation space for two passengers to walk side-by-side and (*b*) most fares just need to be visually inspected.

5. *Determine average passenger service times for each bus door channel and movement.* In the absence of local information, use Exhibit 6-4 (page 6-7) to determine appropriate boarding and alighting service times for the conditions existing at each door channel. When a mix of fare payment options are provided, use the information from Step 2 to create a weighted average service time based on the mix of fare media used. The base values given in Exhibit 6-4 are for non-level boarding with no standees on the bus and should be adjusted as shown in the exhibit notes to reflect level boarding conditions (e.g., boarding from the curb onto a low-floor bus, boarding from a high-level platform onto a high-floor bus) and standees, if present. In addition, when more than 25% of the passenger flow through a single door channel is in the opposite direction of the main flow of passengers, increase both boarding and alighting service times by 20% to account for passenger congestion at the door (*39*).

6. *Determine passenger flow time for each bus door channel.* For a given door channel i, the passenger flow time is

Equation 6-4

$$t_{pf,i} = P_{a,i}t_{a,i} + P_{b,i}t_{b,i}$$

where

$t_{pf,i}$ = passenger flow time for door channel i (s),

$P_{a,i}$ = alighting passengers through door channel i (p),

$t_{a,i}$ = average alighting passenger service time for door channel i (s/p),

$P_{b,i}$ = boarding passengers through door channel i (p), and

$t_{b,i}$ = average boarding passenger service time for door channel i (s/p).

Waiting area LOS is defined in Chapter 10.

7. *Determine the boarding lost time.* If a bus stop only consists of one loading area, boarding lost time is zero. From research (*1*), average boarding lost time for three loading areas is 4 s for more crowded waiting conditions (waiting area LOS C or worse) and 4.5 s for less crowded waiting conditions (waiting area LOS A or B, corresponding to 10 ft²/p [0.9 m²/p] or more within an area centered on the front of the second loading area and extending one-half loading area length to either side).

Analyst judgment should be used to develop boarding lost times for bus stops with 2, 4, or 5 loading areas.

Research has not yet developed boarding lost times for two loading areas—the analyst's judgment should be used to determine how often the second loading area would be used to develop a value between 0 and 4 s. Similarly, research has not yet developed boarding lost times for four or more loading areas, but these would be expected to be significantly longer, given passenger uncertainty about where to wait.

The longest passenger service time of all doors controls dwell time.

8. *Calculate the dwell time.* The dwell time is the time required to serve passengers at the busiest door, plus the time required to open and close the doors, plus any boarding lost time:

Equation 6-5

$$t_d = t_{pf,max} + t_{oc} + t_{bl}$$

where

t_d = average dwell time (s),

$t_{pf,max}$ = maximum passenger flow time of all door channels (s),

t_{oc} = door opening and closing time (s), 2–5 s typical, and

t_{bl} = boarding lost time (s).

Dwell Time Variability

Not all buses stop for the same amount of time at a stop, depending on fluctuations in passenger demand between buses and between routes. In addition, infrequent events such as wheelchair or bicycle loading have the potential to significantly increase a given bus's dwell time at a stop. As discussed earlier in Step 3, dwell time variability is one of the inputs for developing an operating margin that ensures that bus operations at the stop meet a desired level of reliability, by allowing for longer-than-usual dwell times.

The coefficient of variation of dwell times (c_v) is used to measure dwell time variability.

The *coefficient of variation of dwell times* (c_v), the standard deviation of dwell times divided by the average (mean) dwell time, is used to measure dwell time variability. When c_v is zero, all dwell times are the same. When c_v is 1.0, the standard deviation of dwell times is as large as the mean dwell time, meaning that approximately one in three buses will have a dwell time at least twice as large as the average dwell time.

A recommended default value for c_v is 0.6.

Based on field observations of bus dwell times in several U.S. cities (*21*), c_v typically ranges from 0.4 to 0.8, with 0.6 recommended as an appropriate value in the absence of field data.

Impacts of Infrequent Events on Dwell Time

Impact of Wheelchair Movements on Dwell Time

New transit buses in the United States are equipped with wheelchair lifts or ramps. When a lift is in use, the door is blocked from use by other passengers. Typical wheelchair lift cycle times are 60 to 200 s, while the ramps used in low-floor buses reduce the cycle times to 30 to 60 s (including the time required to secure the wheelchair inside the bus). The higher cycle times relate to a small minority of inexperienced or severely disadvantaged users. When wheelchair users regularly use a particular bus stop, the wheelchair lift time should be incorporated into the average dwell time when dwell times are not measured directly. When wheelchair movements are rare, their impact on dwell time is accounted for by dwell time variability.

Impact of Bicycles on Dwell Time

Many U.S. transit agencies provide folding bicycle racks on their buses. When no bicycles are loaded, the racks typically fold upright against the front of the bus. (Rear-mounted racks, bus-towed bicycle trailers, and allowing bicycles on board are less common options.) When bicycles are loaded, passengers deploy the bicycle rack and load their bicycles into one of the available loading positions (typically two or three are provided). The process takes approximately 20 to 30 s. When bicycle rack usage at a stop is frequent enough to warrant special treatment, average bus dwell time is determined using the greater of the passenger service time or the bicycle loading/unloading time. Otherwise, this effect is accounted for by dwell time variability.

Impact of Timepoint Holding on Dwell Time

Some transit agencies' operating practice is to hold buses at timepoints if they are running ahead of schedule. Holding can significantly increase the time a bus spends stopped at a bus stop, which reduces the stop's capacity; however, this factor is not directly accounted for in the dwell time definition, which only includes time to serve passengers and open and close the bus doors. If many buses have to hold at a stop, consideration should be given to adjusting the schedule to reduce the need to hold. If a relatively small number of buses have to hold, the time spent holding can be treated as additional dwell time for the purposes of calculating dwell time variability.

STEP 5: DETERMINE LOADING AREA CAPACITY

Loading Area Capacity Factors

The bus capacity of a loading area is dependent on operating margin, dwell time, clearance time, and traffic signal timing. The first two factors were determined in Steps 3 and 4, respectively. The remaining two factors are discussed in this subsection. The four factors influence loading area capacity as follows:

- The sum of dwell time and clearance time equals the average time a given bus occupies a loading area.
- The operating margin accounts for longer-than-average dwells to ensure that most buses will be able to immediately use the loading area upon arriving.

Dwell time plus clearance time equals the average time a given bus occupies a loading area.

The operating margin provides extra time needed to account for longer-than-average dwells, so that the design failure rate can be achieved.

Loading area capacity is the number of buses per hour that can use a single loading area at a bus stop at the design failure rate.

- The sum of dwell time, clearance time, and operating margin gives the minimum headway between buses needed to limit bus stop failure to the design level, for a bus stop consisting of one loading area. (Multiple loading areas will be addressed in Step 6.)
- Dividing this headway into 3,600 s/h produces the *loading area capacity,* the number of buses per hour that can use a single loading area at a bus stop at the design failure rate.

When the loading area is located at a traffic signal, buses may not be able to leave the loading area immediately after serving passengers (at near-side stops), or enter it immediately (at far-side stops). This requires a few extra considerations:

- The portion of time that the traffic signal permits bus movement is given by the g/C ratio, the ratio of the time the signal is effectively green for buses to the overall length of the traffic signal cycle. Multiplying the g/C ratio by 3,600 gives the number of seconds in an hour that buses are free to enter or leave the stop.
- Dwell time that occurs during the red phase does not impact capacity, as the bus would not have been able to enter or leave the stop during this time. Therefore, only the portion of the dwell time that occurs during green, on average, is used in calculating capacity.

Mathematically, loading area capacity is expressed as (*21*):

Equation 6-6

$$B_l = \frac{3{,}600(g/C)}{t_c + t_d(g/C) + t_{om}} = \frac{3{,}600(g/C)}{t_c + t_d(g/C) + Zc_v t_d}$$

where

B_l = loading area bus capacity (bus/h);

3,600 = number of seconds in 1 hour;

g/C = green time ratio (the ratio of effective green time to total traffic signal cycle length, equals 1.0 for unsignalized streets and bus facilities);

t_c = clearance time (s) = $t_{su} + t_{re}$;

t_{su} = minimum time for a bus to start up, travel its own length, and the next bus to pull into the loading area (s) (default of 10 s);

t_{re} = reentry delay (s), from Exhibit 6-59 or field measured;

t_d = average (mean) dwell time (s);

t_{om} = operating margin (s);

Z = standard normal variable corresponding to a desired failure rate, from Exhibit 6-56; and

c_v = coefficient of variation of dwell times.

Clearance Time

Clearance time calculation.

Clearance time has two components: (*a*) a fixed minimum amount of time for a bus to start up and travel its own length, and for the next bus to pull in and, for off-line stops, (*b*) a potential added amount of time spent waiting for a gap to pull back into traffic, known as *reentry delay*.

Angled loading areas that require buses to back out are rare, but exist. The start-up component of clearance time for these types of loading areas would be considerably longer than 10 s.

Various studies have examined clearance time, with values ranging from 9 to 20 s (*39*). The start-up component of clearance time is about 10 s for a standard bus (*21*). Reentry delay can be measured in the field, estimated from simulation, or estimated using the method given below, which is based on procedures given in the *Highway Capacity Manual 2010* (HCM, *40*).

Reentry delay only needs to be determined for off-line stops—stops where the bus stops out of the traffic lane and must wait for a gap in traffic to pull back into the lane and continue on its route. The following method produces an estimate of maximum average reentry delay, based on the average wait for a suitable gap in randomly arriving traffic, the wait for the queue of vehicles to clear when a traffic signal turns green, or both. The presence of local yield-to-bus laws (and driver compliance with them), local driver courtesy in allowing buses to reenter the street, the aggressiveness of bus drivers in reentering traffic, and the provision of bus queue jumps (for near-side stops at traffic signals) can reduce or eliminate reentry delay. In addition, for near-side stops, to the extent that buses are not ready to depart when the signal turns green, this method's estimate of clearance time will also include a portion of dwell time.

The calculation of reentry delay depends on the bus stop's location relative to traffic signals that can influence traffic patterns in the lane adjacent to the bus stop. One of the following three cases will apply:

1. **Bus stop away from the influence of traffic signals.** When bus stops are located more than 0.25 mi (400 m) away from the nearest upstream signal and outside the influence of a queue from a downstream signal, traffic is assumed to arrive randomly. Buses wait for a suitable gap in traffic to reenter the street.
2. **Bus stop at a traffic signal.** When bus stops are located at a traffic signal, the signal periodically stops traffic moving in the bus's direction. When the light turns green again, the built-up queue of vehicles is released as a platoon that blocks the bus from leaving the stop until the queue clears. During the remainder of the time, until the signal turns yellow, the bus must wait for a gap in traffic.
3. **Bus stop downstream of a traffic signal.** When bus stops are not located at a signalized intersection, but are located within 0.25 mi (400 m) of an upstream signal, traffic patterns will reflect some traffic signal influence, with that influence growing weaker with increasing distance from the signal. Reentry delay will be between that of Case 1 and Case 2.

The following subsections describe how reentry delay is calculated for each case. Tables providing typical reentry delays are provided as an alternative to the equations.

Case 1: Reentry Delay Away from Traffic Signal Influence

In Case 1, traffic is assumed to arrive randomly and the reentry delay is estimated as the average interval between acceptable gaps in traffic. The HCM's unsignalized intersection procedure (right turn from a minor street) (*40*) is used to estimate this delay:

Equation 6-7

$$d_{re,1} = \frac{3{,}600}{c_{re}} + 900\left[\frac{N_{la}}{c_{re}} - 1 + \sqrt{\left(\frac{N_{la}}{c_{re}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{re}}\right)\left(\frac{N_{la}}{c_{re}}\right)}{450}}\right] - 3.3$$

with:

Equation 6-8

$$c_{re} = v\frac{e^{-vt_{ch}/3{,}600}}{1 - e^{-vt_f/3{,}600}}$$

where

$d_{re,1}$ = average reentry delay for Case 1 (s),
c_{re} = capacity of the reentry movement (veh/h),
N_{la} = number of loading areas at the stop,
v = demand flow rate in the curb (rightmost) travel lane (veh/h),
t_{ch} = critical headway for the reentry movement (s) = 7.0 s default,
t_f = follow-up time for the reentry movement (s) = 3.3 s default,
e = exponential function, and
3,600 = number of seconds in an hour.

The critical headway is the minimum headway between vehicles in the adjacent lane that buses can use to reenter traffic; the follow-up time is the time required by a second bus leaving at the same time. The "– 3.3" term in the delay equation adjusts the HCM's control delay for factors unrelated to reentry delay; it represents the calculated HCM delay with an adjacent lane flow rate of 1 veh/h.

Exhibit 6-59 provides the reentry delay values calculated by Equation 6-7 for various traffic volumes in the lane adjacent to the bus stop.

Exhibit 6-59
Average Bus Reentry Delay (Stops Not Near Traffic Signals)

Adjacent Lane Traffic Volume (veh/h)	Average Reentry Delay (s)
1	0
100	1
200	2
300	2
400	3
500	4
600	5
700	6
800	8
900	10
1,000	12

Source: Based on Equation 6-7 using a critical headway of 7.0 s, a follow-up time of 3.3 s, and one loading area.

Case 2: Reentry Delay at Traffic Signals

In Case 2, reentry delay is calculated from (a) the average time to clear the queue of vehicles in the adjacent lane and (b) the average delay waiting for a suitable gap in traffic the remainder of the time.

Queue Service Delay

The time g_s required to service a queue of vehicles that has been stopped for a red light at a traffic signal is (*40*):

$$g_s = \frac{Q_r}{(s_f/3{,}600) - q_g}$$

Equation 6-9

with:

$$Q_r = q_r r$$

Equation 6-10

$$q_r = (1 - p_v)qC/r$$

Equation 6-11

where

- g_s = queue service time for the adjacent lane (s),
- Q_r = queue size at the end of the effective red time (veh),
- s_f = saturation flow rate (veh/s),
- q_g = arrival flow rate during the effective green time (veh/s) = p_v/qCg,
- q_r = arrival flow rate during the effective red time (veh/s),
- p_v = proportion of vehicles arriving during the green indication (decimal) = (g/C) for random arrivals,
- r = effective red time = $C - g$ (s),
- C = traffic signal cycle length (s),
- g = effective green time (s),
- q = arrival flow rate = $v/3{,}600$ (veh/s), and
- v = demand flow rate in the curb (rightmost) travel lane (veh/h).

The saturation flow rate can be calculated using the HCM (*40*) or a default value can be selected from Exhibit 6-60. With random vehicle arrivals, q_r and q_g reduce to the arrival flow rate q; with non-random arrivals, use the HCM to calculate p_v. The queue service delay d_{qs}, in seconds, is the lesser of the queue service time or the effective green time:

$$d_{qs} = min(g_s, g)$$

Equation 6-12

where all variables have been defined previously. This equation caps queue service delay as the length of the green interval: at far-side stops, the signal creates a gap in traffic that the bus can potentially use; at near-side stops, the bus is assumed to pull forward into the intersection on green so that it can proceed when the light turns yellow if no gap has appeared before then.

Exhibit 6-60
Default Through Movement Saturation Flow Rates (veh/h of green)

Region Type	CBD	Non-CBD
Metropolitan (250,000+ population)	1,625	1,800
Other (<250,000 population)	1,500	1,650

Source: HCM 2010 (*40*), based on 3% heavy vehicles, 12 buses stopping per hour, and base saturation flow rates of 1,750 and 1,900 veh/h of green for metropolitan and other region types, respectively.

Note: CBD values can be applied to any location with CBD-like conditions (e.g., higher pedestrian and traffic volumes, constrained roadway geometry).

Exhibit 6-61 provides queue service delay values for a range of adjacent lane traffic demands and traffic signal g/C ratios, assuming a 100-s traffic signal cycle length. For other cycle lengths, the delay values given in the exhibit should be increased or decreased proportionately. Shaded values indicate situations where demand exceeds traffic signal capacity and the queue service delay is capped.

Exhibit 6-61
Illustrative Queue Service Delays (s) (100-s Cycle Length)

Adjacent Lane	*g/C* Ratio								
Traffic Volume (veh/h)	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70
1	0	0	0	0	0	0	0	0	0
100	5	4	4	4	3	3	3	2	2
200	10	9	8	8	7	6	6	5	4
300	16	15	14	12	11	10	9	8	7
400	23	21	20	18	16	15	13	11	10
500	30	29	27	24	22	20	18	16	13
600	30	35	35	32	29	26	23	20	18
700	30	35	40	42	38	34	30	26	23
800	30	35	40	45	48	44	39	34	29
900	30	35	40	45	50	55	50	43	37
1,000	30	35	40	45	50	55	60	56	48

Source: Calculated from Equation 6-9 and Equation 6-12, assuming random arrivals, a 100-s cycle length, and metro CBD conditions.

Note: To calculate queue service delay for other cycle lengths, multiply values in exhibit by (C/100). Shaded values indicate situations where demand exceeds traffic signal capacity and queue service delay is capped by the length of the effective green interval.

Gap-in-Traffic Delay

When a platoon is not present, the situation is similar to Case 1, in that the bus must wait for a suitable gap in traffic. The average delay, in seconds, waiting for a gap in traffic d_{gt} is calculated similarly to reentry delay in Case 1, except that the platooned vehicles over the course of an hour are not included as part of the adjacent lane traffic. An adjusted traffic volume v_{adj}, in vehicles per hour, equal to the total hourly traffic demand in the adjacent lane minus the hourly platooned volume in the adjacent lane, is substituted for v in Exhibit 6-59 or Equation 6-7. Assuming random arrivals, v_{adj} is simply:

Equation 6-13

$$v_{adj} = v(g/C)$$

where all variables have been defined previously.

Reentry Delay for Near-Side Stops

For near-side stops, buses (and traffic in the adjacent lane) can only depart when the signal is green. In this case, reentry delay is the sum of average queue service delay and average gap-in-traffic delay, not to exceed the length of the effective green interval:

Equation 6-14

$$d_{re,2ns} = \min(d_{qs} + d_{gt}, g)$$

where $d_{re,2ns}$ is the reentry delay for near-side stops in Case 2, in seconds, and all other variables are as defined previously.

Reentry Delay for Far-Side Stops

At far-side stops, buses can depart at any time traffic in the adjacent lane permits. Reentry delay is the average of queue service delay and gap-in-traffic delay, weighted by the proportion of time each condition occurs:

$$d_{re,2fs} = d_{qs}\frac{d_{qs}}{C} + d_{gt}\frac{(C - d_{qs})}{C}$$

Equation 6-15

where $d_{re,2fs}$ is the reentry delay for far-side stops in Case 2, in seconds, and all other variables are as defined previously.

Case 3: Reentry Delay Downstream from Traffic Signals

In Case 3, traffic patterns are partially influenced by the upstream signal. In this case, reentry delay is calculated from both the Case 1 reentry delay and the Case 2 far-side reentry delay, giving greater weight to the Case 2 delay the closer the bus stop is to the traffic signal:

$$d_{re,3} = d_{re,2fs} - \frac{D_{bs}(d_{re,2fs} - d_{re,1})}{D_{max}}$$

Equation 6-16

where

$d_{re,3}$ = reentry delay for Case 3 (s),

$d_{re,2fs}$ = reentry delay for Case 2, far-side stop (s),

$d_{re,1}$ = reentry delay for Case 1 (s),

D_{bs} = bus stop distance from the nearest upstream traffic signal (mi, m), and

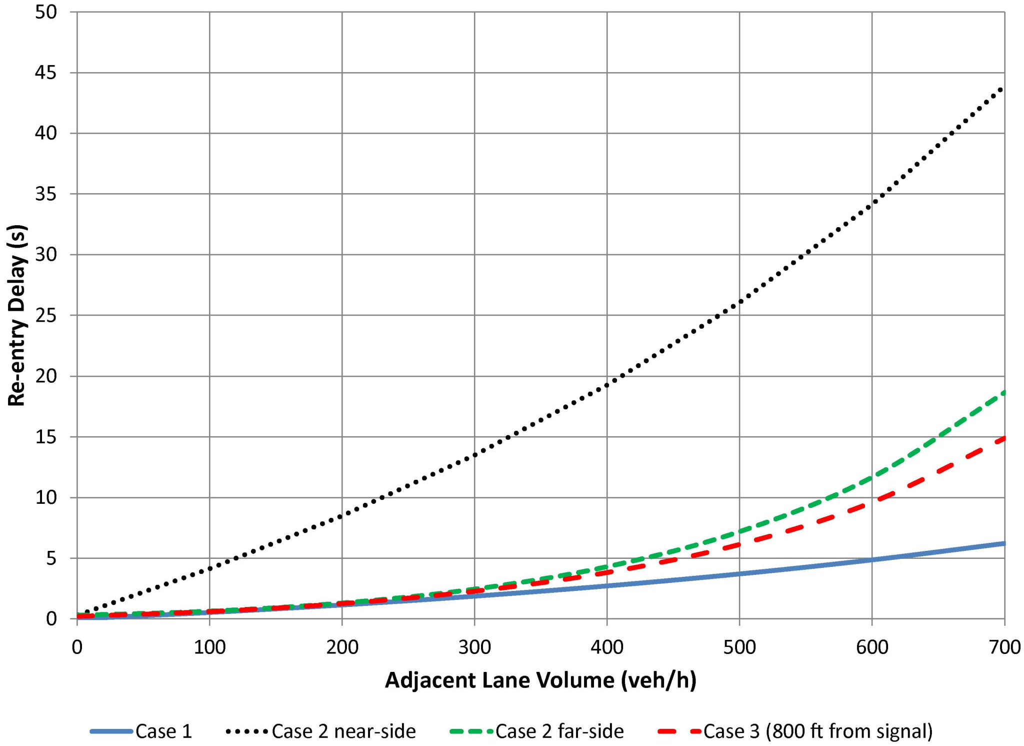
D_{max} = maximum distance for Case 3 (0.25 mi, 400 m).

Summary

Reentry delay is zero when buses stop in the traffic lane to serve passengers, or are provided with a queue jump at a traffic signal. In other situations, reentry delay is lower with any of the following: lower traffic volumes in the adjacent lane, shorter traffic signal cycles, greater green time provided for the bus' direction of travel, and increasing bus stop distance downstream from an intersection.

Exhibit 6-62 illustrates the reentry delay associated with different bus stop locations for the conditions given in the exhibit.

Exhibit 6-62
Illustrative Reentry Delay by Case



Source: Calculated.
Note: Assumes 100-s cycle length, g/C = 0.45, random arrivals, and metro CBD conditions.

STEP 6: DETERMINE BUS STOP CAPACITY

Overview

A bus stop's capacity depends on the capacities of the bus stop's individual loading areas (determined in Step 5), the number of loading areas provided, the design of those loading areas, and the bus stop's position relative to the roadway. It is also dependent on traffic congestion that interferes with a bus's access to the stop and on bus stopping patterns.

Step 6a: Determine the Number of Effective Loading Areas

As discussed earlier in the chapter, the majority of on-street bus stops use linear loading areas. Depending on how closely buses stop near to each other in adjacent linear loading areas, buses *may* be able to exit loading areas independently; however, in constrained situations, they need to wait for the bus(es) in front of them to depart before they can depart. Furthermore, as was illustrated in Exhibit 6-13, upon entering a bus stop consisting of multiple loading areas, a bus will stop at the forward-most available stop. If another bus is occupying one of the stop's loading areas, the arriving bus will need to stop behind it, potentially leaving loading areas farther ahead unoccupied because they cannot be accessed at that point in time.

Because buses can temporarily block loading areas from other buses, there is a diminishing-returns effect when using additional linear loading areas to add capacity to a bus stop. The more loading areas that are added, the more likely that some of them will be inaccessible at a given point in time. The concept of *effective loading areas* is used to describe this effect, where the second linear loading area provides less capacity than the first, the third adds even less, and so on.

The incremental increase in capacity provided by each additional linear loading area depends on whether the loading areas are located on-line or off-line, as well as on the arrival characteristics of the buses using the stop. Field observations indicate that linear loading areas are used more efficiently when buses enter and exit them as *platoons*, groups of 2 to 3 buses with similar dwell times (or, at least, dwell times short enough to be completed by the time a traffic signal turns green) that travel down the street together. Platoons can be formed by upstream traffic signals or by intentionally scheduling groups of buses to leave the start of a route together, requiring a staging area near the locations where most passengers will board.

Exhibit 6-63 provides efficiency factors for linear loading areas. Non-linear loading areas are 100% efficient—the number of effective loading areas equals the number of physical loading areas. The off-line loading area efficiency factors given in the exhibit were originally developed based on experience at the Port Authority of New York and New Jersey's Midtown Bus Terminal (*17*), but have also been observed on an Australian busway (*1*). The on-line loading efficiency factors are based on simulation (*37*) and European experience (*41*).

Exhibit 6-63 Efficiency of Multiple Linear Loading Areas at Bus Stops

	On-Line Loading Areas				Off-Line Loading Areas	
	Random Arrivals		Platooned Arrivals		All Arrivals	
Loading Area #	Efficiency %	Cumulative # of Effective Loading Areas	Efficiency %	Cumulative # of Effective Loading Areas	Efficiency %	Cumulative # of Effective Loading Areas
1	100	1.00	100	1.00	100	1.00
2	75	1.75	85	1.85	85	1.85
3	70	2.45	80	2.65	75	2.60
4	20	2.65	25	2.90	65	3.25
5	10	2.75	10	3.00	50	3.75

Sources: *TCRP Report 26* (*21*) and *TCRP Research Results Digest 38* (*37*).
Notes: On-line values assume that buses do not overtake each other.
Values apply only to linear loading areas; non-linear designs are 100% effective.

Exhibit 6-63 suggests that four or five on-line linear loading areas provide the effective capacity of no more than three loading areas. When additional capacity is required, other options that can be considered include:

- Constructing sawtooth loading areas, a non-linear design that allows buses to enter and exit loading areas independently of each other. This type of design requires approximately 33% more length per loading area than a linear design, but provides the full capacity benefit of each loading area and also offers the option of assigning specific loading areas to specific routes, which is convenient for passengers and eliminates boarding lost time. This design has been used at some stations on the Miami-Dade Transitway (*7*).
- Splitting the bus stop into two or more adjacent stops, each with 2 to 3 linear loading areas, and assigning particular routes to particular stops, but not to specific loading areas within each stop. This is an example of a skip-stop operation. This design has been used on downtown streets with high bus volumes in Denver, Minneapolis, and Portland, but could also be applied to

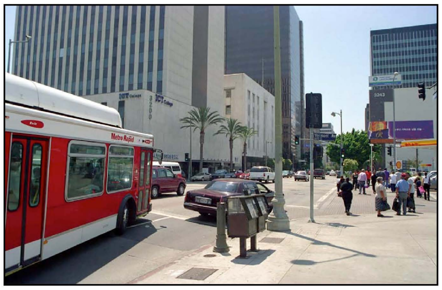
busway operations (at the expense of requiring more space and additional signage at each station directing passengers to the appropriate platform).

Step 6b: Adjust Capacity for Traffic Blockage at Traffic Signals

Turning movements at intersections with bus stops reduce bus stop capacity.

Vehicular traffic competes with buses for space at an intersection (Exhibit 6-64). Vehicles turning from the bus' lane (or across the bus' path, at off-line stops) may use up signal green time that would otherwise have been available for bus movement as these vehicles wait for conflicting vehicles and pedestrians to clear before they can complete their turn. The reduced green time available to buses reduces, in turn, the bus stop capacity. The impact on bus stop capacity depends on (*a*) the movement's traffic volume relative to its capacity, (*b*) the bus stop location (e.g., near side, far side), and (*c*) the ability or inability of buses to move around turning vehicles. If other vehicles are not allowed to use the bus facility (e.g., a busway, a freeway managed lane, an exclusive bus lane that does not allow general traffic to turn from the lane), there is no traffic blockage impact on capacity and this step can be skipped. Similarly, if the stop in question is located more than one-half block away from a traffic signal, and outside the influence of a queue of stopped vehicles generated by the signal, this step can be skipped.

Exhibit 6-64
Examples of Auto Turning Conflicts with Buses



(a) Los Angeles (right turn)

(b) Portland (left turn)

The capacity of through movements in the curb lane c_{th} (in vehicles per hour) is the lane's saturation flow rate times the g/C ratio. The saturation flow rate can be calculated using the HCM (*40*) or estimated from Exhibit 6-60.

Exhibit 6-65 can be used to estimate the capacity of right-turn movements c_{rt} based on ranges of conflicting pedestrian volumes and the proportion of effective green time available for traffic.

Exhibit 6-65
Right-Turn Vehicle Capacities c_{rt} for Planning Applications (veh/h)

Conflicting Pedestrian Volume (ped/h)	g/C Ratio for Curb Lane					
	0.35	0.40	0.45	0.50	0.55	0.60
0	510	580	650	730	800	870
100	440	510	580	650	730	800
200	360	440	510	580	650	730
400	220	290	360	440	510	580
600	70	150	220	290	360	440
800	*	*	70	150	220	290
1,000	*	*	*	*	70	150

Source: HCM 2010 (*40*), based on 1,450 × (g/C) × (1 – (pedestrian volume/2,000)) with PHF=1.
Note: *Vehicles can only turn at the end of green, assume one or two per traffic signal cycle. Values shown are for CBD locations, multiply by 1.1 for other locations.

The curb lane capacity c_{cl}, in vehicles per hour, is the average of the through and right-turn capacities, weighted by their respective volumes. The effects of traffic blockage reduce bus capacity in proportion to the following adjustment factor f_{tb} (*21*):

$$f_{tb} = 1 - f_l \left(\frac{v_{cl}}{c_{cl}} \right)$$

Equation 6-17

where

f_{tb} = traffic blockage adjustment factor;

f_l = bus stop location factor, from Exhibit 6-66;

v_{cl} = curb lane traffic volume at intersection (veh/h); and

c_{cl} = curb lane capacity at intersection (veh/h).

Values of the bus stop location factor f_l are given in Exhibit 6-66. This factor reflects the likely ability of buses to move around right-turning traffic. Where right turns are allowed, the factor ranges from 0.5 (for a far-side stop with the adjacent lane available for buses) to 1.0 (for a near-side stop with all buses restricted to a single lane). A factor of 0.0 is used for Type 3 lanes, as right turns are not allowed by non-transit vehicles from this type of lane, automatically making f_{tb} equal to 1 for Type 3 lanes.

Exhibit 6-66
Bus Stop Location Factor f_l

	Lane Type		
Bus Stop Location	**Type 1**	**Type 2**	**Type 3**
Near side	1.0	0.9	0.0
Mid-block before or after traffic signal	0.9	0.7	0.0
Far side	0.8	0.5	0.0

Source: *TCRP Report 26* (*21*).
Note: f_l = 0.0 for contraflow bus lanes, median busways, and grade-separated busways regardless of bus stop location or lane type, as right turns are either prohibited or do not interfere with bus operations.

Step 6c: Calculate Bus Stop Capacity

Bus stop capacity is the capacity of a single loading area multiplied by the number of effective loading areas and the traffic blockage adjustment factor:

$$B_s = N_{el} B_l f_{tb} = N_{el} f_{tb} \frac{3{,}600(g/C)}{t_c + t_d(g/C) + Z c_v t_d}$$

Equation 6-18

where B_s is the bus stop capacity (bus/h), N_{el} is the number of effective loading areas at the bus stop, and all other variables as defined previously.

STEP 7: DETERMINE FACILITY BUS CAPACITY

Overview

Bus facility capacity is greatly dependent on the exclusivity of the facility—the less interference that buses have from other traffic, the greater the capacity. When the majority of buses make no stops along a facility (e.g., express services to downtown), and passing lanes are provided at any stops that do exist, a bus facility acts like a pipe that can serve hundreds of buses per hour. For example, up to 280 peak-direction buses per hour travel on the busiest portions of Bogotá's TransMilenio BRT system (*42*) and 735 buses per hour operate on the New Jersey approach to the Lincoln Tunnel into New York City (*43*). In these cases, the facility itself does not constrain capacity; rather, the capacity of other bus facilities before or after the non-stop section (e.g., downtown streets in Ottawa), or the capacity of the bus terminal(s) where the buses end up (e.g., the Port Authority bus terminal in New York City) constrain the number of buses that can be operated on the facility. Use Step 7a to determine the capacity of these facilities.

More typically, even when different service types (e.g., local, limited stop) are operated along a facility, there will be common stops (or groups of stops, with skip-stop operation) served by all buses using the facility. In this case, the facility capacity will be constrained by the capacity of the *critical bus stop*—the bus stop (or group of stops) used by all buses that has the lowest capacity. Use either Step 7b (no skip stops) or Step 7c (skip-stop operation) to determine the capacity of these facilities.

It is also important to compare the capacity of each bus stop along the facility to the number of buses scheduled or planned to use that stop, as operational problems can develop anywhere along a facility when the number of buses stopping at a particular stop exceeds the stop's capacity. Step 7d describes this process.

Step 7a: Non-stop Facility Capacity

Non-stop facilities include freeway managed lanes and busways where passing lanes are provided at stations. Determining the number of buses that can be operated along these facilities requires examining both the facility itself and the facilities and terminals serving it for the constraining location. Potential constraints include:

- A busway station where a passing lane is not provided (e.g., due to right-of-way constraints). Use the procedure given in Step 7b to determine the station's capacity, assigning a zero dwell time to those buses not making passenger stops at the station.
- Facility capacity used by other vehicles (e.g., high-occupancy vehicles on freeway managed lanes). At the time of writing, NCHRP Project 3-96 was developing a method for assessing the capacity and performance of managed lanes. Simulation can also be used to estimate the number of buses and other vehicles that can operate on a managed lane at a desired level of service.
- A low-capacity intersection located before or after the facility being analyzed that constrains bus throughput (for example, a signalized left-turn movement). The HCM (*40*) can be used to evaluate its capacity.
- The combined bus capacity of the terminal(s), transit center(s), and/or streets that buses on the non-stop facility end up. Use the bus stop capacity method given in Step 6 to determine the bus capacity of a terminal or transit center, with appropriate adjustments to dwell time to account for any layover activity that may occur. Use the procedure given in Step 7b to determine the bus capacity of the streets buses serve following the non-stop facility.

The lowest capacity resulting from these checks will serve as the capacity constraint for the non-stop facility.

Step 7b: Facility Capacity without Skip-Stop Operation

When skip-stop operation is not used along a bus facility, the facility capacity is equal to the capacity of the *critical stop* along the facility. When all buses using the facility stop at all stops, the critical stop is the bus stop with the lowest capacity. When a mix of service types (e.g., local and limited stop) uses the facility, the critical stop will be the bus stop used by all service types that has the lowest capacity.

Step 7c: Facility Capacity with Skip-Stop Operation

When skip-stop operation is used, the bus facility capacity is equal to the sum of the capacities of the critical bus stops of each skip-stop group, multiplied by an adjustment factor f_k reflecting inefficient arrival patterns and the effects of high vehicular traffic volumes in the adjacent lane (*21*):

$$B = f_k(B_1 + B_2 + \cdots + B_n)$$

Equation 6-19

where

B = bus facility design capacity (bus/h);

f_k = capacity adjustment factor for skip-stop operations, from Equation 6-20; and

$B_1 \ldots B_n$ = critical bus stop capacity of a given skip-stop pattern (bus/h);

with

$$f_k = \frac{1 + f_a f_i (N_{ss} - 1)}{N_{ss}}$$

Equation 6-20

where

f_a = arrival-type factor, reflecting the ability to fully utilize the bus stops in a skip-stop operation:

= 0.50 for random arrivals (poor scheduling/poor schedule adherence),

= 0.75 for typical arrivals (imperfect schedule adherence), and

= 1.00 for platooned arrivals (buses travel in groups, like cars of a train);

f_i = adjacent lane impedance factor, from Equation 6-21; and

N_{ss} = number of alternating skip stops in sequence;

and with

$$f_i = 1 - 0.8\left(\frac{v_{al}}{c_{al}}\right)^3$$

Equation 6-21

where

v_{al} = traffic volume in the adjacent lane (veh/h); and

c_{al} = capacity of the adjacent lane (veh/h).

A planning-level estimate of the adjacent lane capacity can be made by multiplying the typical downtown lane vehicle saturation flow rate of 1,750 vehicles per lane per hour of green by the g/C ratio of the bus lane. Outside the downtown area, a saturation flow rate of 1,600 vehicles per lane per hour of green may be used. Consult the HCM (*40*) if a more detailed estimate of adjacent lane capacity is required.

The values provided by Equation 6-20 and Equation 6-21 result in added capacity with skip-stop operation, even when the adjacent lane is fully utilized by other vehicles, since non-stopping buses have zero dwell time at the stop. When there is no spreading of stops, there is no increase in capacity rendered by the adjacent lane, as all buses must stop at every stop.

Exhibit 6-67 gives representative values of the adjustment factor f_k for various lane types, bus arrival types, and bus stopping patterns. As indicated previously, these values are applied to the *sum* of the capacities in the sequence of bus stops. Thus, they reflect the actual dwell times at each stop. Exhibit 6-68 gives factors for a Type 2 bus lane with two-block alternating stops.

Exhibit 6-67
Typical Values of Adjustment Factor f_k for Availability of Adjacent Lanes

Condition	Adjacent Lane v/c	f_l	N_{ss} - 1	f_a	f_k
TYPE 1 LANE					
Stops every block	0 to 1	0 to 1	0	0.00	1.00
TYPE 2 LANE					
Stops every block	0 to 1	0 to 1	0	0.00	1.00
Alternating 2-block stops, random	0	1	1	0.50	0.75
	1	0.2*	1	0.50	0.55
Alternating 2-block stops, typical	0	1	1	0.75	0.88
	1	0.2*	1	0.75	0.58
Alternating 2-block stops, platooned	0	1	1	1.00	1.00
	1	0.2*	1	1.00	0.60
TYPE 3 LANE					
Alternating 2-block stops, random	0	1	1	0.50	0.75
Alternating 2-block stops, typical	0	1	1	0.75	0.88
Alternating 2-block stops, platooned	0	1	1	1.00	1.00
Alternating 3-block stops, random	0	1	2	0.50	0.67
Alternating 3-block stops, typical	0	1	2	0.75	0.83
Alternating 3-block stops, platooned	0	1	2	1.00	1.00

Source: *TCRP Report 26* (*21*).
Notes: * approximate
v/c = volume-to-capacity ratio.

Exhibit 6-68
Values of Adjustment Factor f_k for Type 2 Bus Lanes with Alternate Two-Block Skip-Stops

Adjacent Lane v/c	Arrival Pattern: Random	Typical	Platooned
0.0	0.75	0.88	1.00
0.5	0.72	0.84	0.95
0.6	0.71	0.81	0.92
0.7	0.68	0.77	0.87
0.8	0.65	0.71	0.80
0.9	0.60	0.65	0.71
1.0	0.55	0.58	0.60

Source: *TCRP Report 26* (*21*).
Note: *v/c* = volume-to-capacity ratio.

Step 7d: Check *v/c* Ratios of All Stops along the Facility

When a mix of stopping patterns is used, stops other than the critical stop may have capacity problems.

Even when the critical bus stop provides sufficient capacity for the scheduled or planned number of buses using the facility, other bus stops may not provide sufficient capacity to serve even the reduced number of buses using those stops. Therefore, the scheduled or planned volume of buses at each bus stop should be compared to the stop's capacity. If the volume exceeds the capacity, buses will queue behind the stop, resulting in poor bus speeds, schedule reliability problems, and potential traffic operations issues.

The capacities determined in Steps 5–7 are hourly capacities that assume that bus arrivals are spread out over the course of the hour. If bus arrivals are more concentrated during a particular portion of the hour (e.g., peaking over a 15- or 30-min period), volumes and capacities should also be checked during those peak-of-the-peak periods. For example, dividing the hourly capacity by 4 gives the maximum number of buses a loading area, bus stop, or facility can accommodate in a given 15-min period.

Steps 5–7 calculate hourly capacities. It may also be necessary to compare volume to capacity for shorter time periods.

STEP 8: DETERMINE FACILITY PERSON CAPACITY

The final step is to determine how many persons can be served by the bus facility over the course of an hour. As discussed in Section 2, person capacity is influenced by the following:

- The facility's bus capacity,
- Transit agency policy regarding passenger loads,
- Scheduled headways, and
- Passenger demand diversity.

Scheduled Person Capacity

Scheduled person capacity reflects the number of passengers that can be carried through the facility's maximum load section, given the existing schedule and bus model(s) used. If a transit agency's policy is that passenger loading should not exceed P_{max} passengers per bus model *on average* during an hour, scheduled person capacity is calculated as follows:

$$P_s = \sum_{i=1}^{N_{bm}} P_{max,i} N_i$$

Equation 6-22

where

P_s = scheduled person capacity (p/h),

$P_{max,i}$ = maximum schedule load for bus model i (p/bus),

N_{bm} = number of different bus models operated on the facility, and

N_i = number of buses of bus model i scheduled to use the facility during the hour (bus/h).

If a transit agency's policy is that passenger loading should *not regularly exceed* P_{max} passengers per bus model during an hour, scheduled person capacity is calculated as follows:

$$P_s = \sum_{i=1}^{n} P_{max,i} (PHF) N_i$$

Equation 6-23

where *PHF* is the peak-hour factor and all other variables are as defined previously. The addition of *PHF* reduces person capacity to a level that results in buses operating at, but not generally above, the maximum schedule load during the peak 15 min and at somewhat reduced loading levels during the remainder of the hour.

PHF *values range from 0.25 (all passenger demand occurs during a single 15-min period in an hour) to 1.00 (demand is constant throughout the hour).*

Typical peak-hour factors range from 0.60 to 0.95 for transit lines (*39*, *44*). In the absence of other information, 0.75 may be used as a default PHF for bus service where the schedule is not adjusted to accommodate peaks in demand (e.g., when clock headways are used). When headways are adjusted to serve predictable peaks in demand, a PHF of 0.85 may be used as a default.

When available, a *PHF* value representative of actual route- or facility-specific conditions is preferred to a default value. APC data can be used in conjunction with Equation 6-24 to determine a local value for *PHF.* If buses operate at longer than 15-min headways, the denominator of Equation 6-24 should be adjusted appropriately (e.g., $3P_{20}$ for 20-min headways).

Equation 6-24

$$PHF = \frac{P_h}{4P_{15}}$$

where

PHF = peak-hour factor;

P_h = passenger volume during the peak hour (p); and

P_{15} = passenger volume during the peak 15 min (p).

Design Person Capacity

Design person capacity is the number of people that *could* be carried through the facility's maximum load section, if buses were scheduled to use the facility at its full capacity, under a specified set of conditions (e.g., design failure rate, vehicle types, fare collection method). In this case, Equation 6-22 and Equation 6-23 are replaced with the following, depending on whether the loading standard is an average (Equation 6-25) or is not to be regularly exceeded (Equation 6-26):

Equation 6-25

$$P = P_{max}B$$

Equation 6-26

$$P = P_{max}(PHF)B$$

where

P = design person capacity (p/h),

P_{max} = weighted average maximum schedule load for buses using the facility (p/bus), and

B = bus facility design capacity (bus/h).

6. BUS SPEED METHODOLOGY

This section presents a computational methodology for estimating bus speeds on all types of bus facilities except freeway managed lanes. Exhibit 6-69 shows the steps involved in applying the methodology.

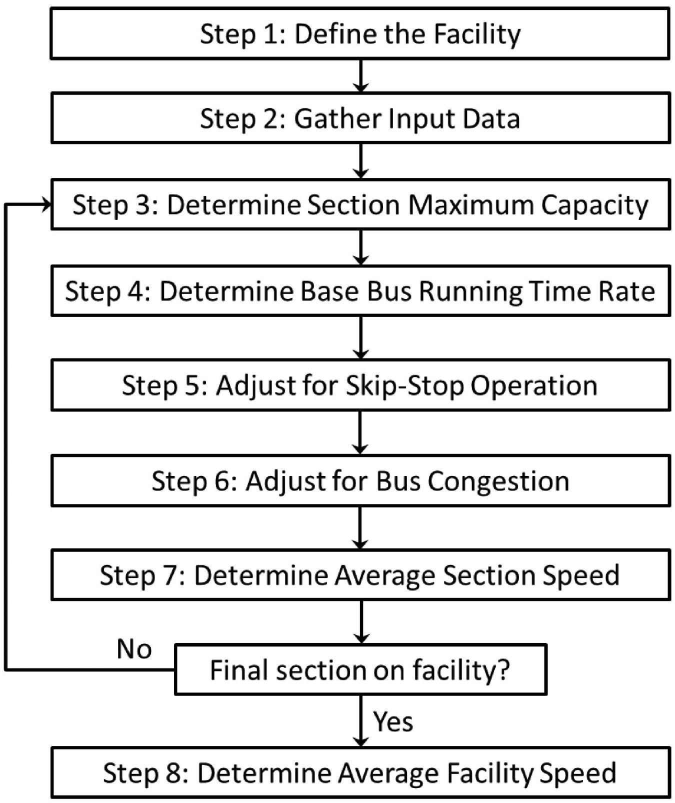


Exhibit 6-69 Bus Speed Methodology Flowchart

The core of the methodology is based on research on arterial street bus lanes presented in *TCRP Report 26* (*21*), which investigated the operation of arterial street bus lanes in a number of North American cities, with modifications made for the TCQSM 3rd Edition to allow unimpeded bus travel time rates to be calculated directly, if desired. The methodology is suitable for developing a planning-level estimate of the average bus speed along a bus facility for a given set of conditions.

If intersection-level traffic volume and traffic signal timing data are available for the facility, the HCM's urban streets methodology (*40*) can be substituted in Step 4 to provide an operations-level estimate of traffic and traffic signal delays, while remaining consistent with the basic TCQSM methodology.

STEP 1: DEFINE THE FACILITY

The facility is defined the same way as described in Section 5, Bus Capacity Methodology. Once the overall facility is defined, it must be divided into sections with similar right-of-way types (e.g., busway with passing lanes, Type 2 arterial bus lane, Type 1 mixed-traffic operation), stop spacing, and dwell times. Average speed will be calculated first for each individual section and then combined into the overall facility speed at the end of the process. Sections should be at least 0.25 mi (400 m) and preferably 0.5 mi (800 m) long.

STEP 2: GATHER INPUT DATA

All of the input data described in Section 5 for calculating bus capacity are required. In addition, the following data are required for each section of the facility:

- Average stop spacing (stop/mi, stop/km);
- Average dwell time (s/bus/stop);
- Scheduled number of buses at the critical stop(s) (bus/h);
- Traffic signal timing and spacing (typical, signals set for bus progression, signals more frequent than bus stops); and
- Traffic interference (general traffic prohibited, bus lane with right-turn lanes, bus lane with traffic/parking blockage, mixed traffic).

STEP 3: DETERMINE SECTION MAXIMUM CAPACITY

In this step, apply the capacity methodology described in Section 5 with the following adjustments:

1. Each section should be treated as its own facility for the purpose of calculating capacity.
2. A 25% failure rate should be used to estimate maximum capacity. The bus–bus interference factor used in Step 6 below adjusts for conditions that might result in bus stop failure.

Use a 25% failure rate when estimating a section's maximum capacity.

STEP 4: DETERMINE BASE BUS RUNNING TIME RATE

The HCM's urban street transit speed estimation method can be substituted for Step 4 when intersection-level traffic volume and signal timing data are available.

Step 4 estimates a travel time rate in minutes per mile or kilometer, based on the bus's running speed between stops, stop spacing, and delays due to traffic interference. Steps 5 and 6 develop adjustment factors that reflect the impacts of skip-stop operation and bus congestion, respectively, and overall bus speeds. As mentioned in this section's introduction, the HCM's urban street transit speed estimation method (*40*) can be substituted for this step when intersection-level traffic volume and signal timing data are available.

Step 4a: Calculate the Unimpeded Bus Running Time Rate

This step calculates the travel time rate a bus would experience if it could travel along the facility without traffic signal or traffic delays. The unimpeded travel time rate incorporates the average dwell time of all bus stops in the section, the acceleration and deceleration delays associated with each stop, and the time spent traveling at the bus's running speed for the facility (typically, the facility's speed limit).

The acceleration and deceleration time per stop is the time spent slowing from the facility's running speed to a stop and accelerating back to running speed.

$$t_{acc} = \frac{c_f v_{run}}{a}$$

Equation 6-27

$$t_{dec} = \frac{c_f v_{run}}{d}$$

Equation 6-28

where

t_{acc} = acceleration time (s/stop);

t_{dec} = deceleration time (s/stop);

c_f = conversion factor = 1.47 (5,280 ft/mi / 3,600 s/h) or 0.278 (1,000 m/km / 3,600 s/h);

v_{run} = bus running speed on the facility, typically the posted speed (mi/h, km/h);

a = average bus acceleration rate to running speed (ft/s^2, m/s^2); and

d = average bus deceleration rate from running speed (ft/s^2, m/s^2).

These equations assume that buses stop at each stop within the section. In the case of a busway with express bus service where buses slow, but do not stop within each station, ($v_{run} - v_{st}$) can be substituted for v_{run} in Equation 6-27 and Equation 6-28, where v_{st} is the bus travel speed through the station (greater than zero), measured in miles per hour or kilometers per hour. The time required to travel through the station is:

$$t_{sta} = \frac{L_{sta}}{\frac{1}{c_f v_{st}} - \frac{1}{c_f v_{run}}}$$

Equation 6-29

where t_{sta} is the station travel time in seconds per stop, L_{sta} is the length of the station speed zone in feet or meters, and all other variables are as defined previously.

The total distance traveled at less than running speed L_{ad} (in feet or meters per stop) associated with each stop or station is:

$$L_{ad} = 0.5at_{acc}^2 + 0.5dt_{dec}^2 + L_{sta}$$

Equation 6-30

where all variables have been defined previously. If L_{ad} multiplied by the average stop spacing is greater than 5,280 ft or 1,000 m, then a bus cannot fully accelerate to the selected facility running speed before it must begin decelerating again to the next stop. In this case, a new (lower) value for v_{run} must be selected and the process repeated beginning with Equation 6-27.

Check to make sure that the bus can reach the selected running speed before decelerating to the next stop.

The total distance travelled at running speed per mile or kilometer is:

$$L_{rs} = L_{mk} - N_s L_{ad}$$

Equation 6-31

where

L_{rs} = distance traveled at running speed per mile or kilometer (ft, m),

L_{mk} = length of a mile or kilometer (5,280 ft, 1,000 m),

N_s = average stop spacing (stops/mi, stops/km), and

L_{ad} = distance traveled at less than running speed (ft/stop, m/stop).

Finally, the time spent traveling at running speed (t_{rs}, in seconds per mile or kilometer) is:

Equation 6-32

$$t_{rs} = \frac{L_{rs}}{c_f v_{run}}$$

where all variables have been defined previously.

The unimpeded running time rate is the sum of the time spent at running speed plus the sum of the average dwell time and acceleration and deceleration times associated with each bus stop:

Equation 6-33

$$t_u = \frac{t_{rs} + N_s(t_{dt} + t_{acc} + t_{dec} + t_{sta})}{60}$$

where

t_u = unimpeded running time rate (min/mi, min/km),
t_{rs} = time spent at running speed (s/mi, s/km),
N_s = average stop spacing (stops/mi, stops/km),
t_{dt} = average dwell time of all stops within the section (s/stop),
t_{acc} = acceleration time (s/stop),
t_{dec} = deceleration time (s/stop),
t_{sta} = station travel time for buses slowing but not stopping at the bus stop (s/stop), and
60 = number of seconds per minute.

The average dwell time used here is the average of all stops along the section, rather than the average critical stop dwell time used for capacity analysis.

The following three exhibits provide representative values of the unimpeded running time rate for CBD conditions (Exhibit 6-70), suburban conditions (Exhibit 6-71), and busways (Exhibit 6-73).

Exhibit 6-70
Illustrative Unimpeded Running Time Rates (min/mi): CBD

Average	Stops per mile							
Dwell Time (s)	2	4	5	6	7	8	10	12
10	3.06	3.73	4.06	4.39	4.73	5.06	5.73	6.39
20	3.39	4.39	4.89	5.39	5.89	6.39	7.39	8.39
30	3.73	5.06	5.73	6.39	7.06	7.73	9.06	10.39
40	4.06	5.73	6.56	7.39	8.23	9.06	10.73	12.39
50	4.39	6.39	7.39	8.39	9.39	10.39	12.39	14.39
60	4.73	7.06	8.23	9.39	10.56	11.73	14.06	16.39

Source: Calculated.
Note: Assumes 25 mi/h running speed, 3.4 ft^2/s average acceleration rate, and 4.0 ft^2/s deceleration rate.

Exhibit 6-71
Illustrative Unimpeded Running Time Rates (min/mi): Suburban Arterial

Average	Stops per mile				
Dwell Time (s)	2	3	4	5	6
10	2.56	2.99	3.42	3.85	4.27
15	2.73	3.24	3.75	4.26	4.77
20	2.90	3.49	4.08	4.68	5.27
25	3.06	3.74	4.42	5.10	5.77
30	3.23	3.99	4.75	5.51	6.27

Source: Calculated.
Note: Assumes 35 mi/h running speed, 2.8 ft^2/s average acceleration rate, and 4.0 ft^2/s deceleration rate.

Exhibit 6-72 Illustrative Unimpeded Running Time Rates (min/mi): Busway

Average Dwell Time (s)	Stops per mile 0.5	1	1.5	2	2.5
0	1.38	1.56	1.75	1.93	2.11
15	1.56	1.88	2.22	2.56	2.90
30	1.75	2.13	2.60	3.06	3.53
45	1.93	2.38	2.97	3.56	4.15
60	2.11	2.63	3.35	4.06	4.78

Source: Calculated.
Notes: Assumes 50 mi/h running speed, 2.2 ft^2/s average acceleration rate, and 4.0 ft^2/s deceleration rate. Use the 0 dwell time row for express buses slowing, but not stopping at stations (25 mi/h station speed limit and 325-ft-long speed zone through station assumed). Assumes passing lane available for non-stopping buses and no at-grade pedestrian crossings within the station.

Step 4b: Calculate Additional Running Time Losses

Step 4b can be skipped when analyzing grade-separated busways.

This step calculates the additional average delay a bus incurs while traveling along a street or bus facility due to traffic signals and interference from other vehicles sharing the lane with the bus. This step can be skipped for grade-separated busways, as these interferences do not exist.

Exhibit 6-73 provides estimates of additional running time losses t_l (in minutes per mile) on urban bus facilities, accounting for the effects of signals and other traffic sharing the bus lane. These values were derived from field observations (*37*). When applying Exhibit 6-73, the additional running time loss selected from a possible range of losses should consider both the quality of traffic signal progression and enforcement efforts (or the lack thereof) to keep non-authorized vehicles out of a bus lane. A calibrated version of this exhibit could be developed for a given city (for example, by analyzing AVL data) by comparing actual bus speeds under selected conditions to the unimpeded speed—the difference in speeds reflects the additional running time loss. In addition, the HCM's urban streets method (*40*) can be used to develop a more precise estimate of traffic and traffic signal delays.

Exhibit 6-73 Estimated Bus Running Time Losses t_l on Urban Streets (min/mi)

Condition	Bus Lane	Bus Lane, No Right Turns	Bus Lane With Right Turn Delays	Bus Lanes Blocked by Traffic	Mixed Traffic Flow
CENTRAL BUSINESS DISTRICT					
Typical		1.2	2.0	2.5–3.0	3.0
Signals set for buses		0.6	1.4		
Signals more frequent than bus stops		1.5–2.0	2.5–3.0	3.0–3.5	3.5–4.0
ARTERIAL ROADWAYS OUTSIDE THE CBD					
Typical	0.7				1.0
Range	0.5–1.0				0.7–1.5

Source: *TCRP Research Results Digest 38* (*37*).
Notes: Traffic delays reflect peak conditions.
A metric version of this exhibit appears in Appendix A.

Step 4c: Calculate the Base Bus Running Time Rate

The base bus running time t_r (in minutes per mile or kilometer) is the sum of the unimpeded running time t_u and the additional running time losses t_l:

Equation 6-34

$$t_r = t_u + t_l$$

STEP 5: ADJUST FOR SKIP-STOP OPERATION

Skip-stop operation spreads buses out among a series of bus stops, allowing for an increase in speeds. The analytical procedure accounts for the skip-stop operations by considering only the bus stops in the skip-stop pattern. For example, if bus stops are located 400 ft (125 m) apart (say a stop at each intersection), a two-block skip-stop pattern provides 800 ft (250 m) between stops for a bus using that pattern. A bus with a two-block stop pattern would be able to proceed faster than a bus with a one-block stop pattern. However, some of this increase will be offset by increases in dwell times, as each stop will have to accommodate more passengers.

The ability of buses to leave the curb lane to pass stopped vehicles is another factor in the ability to attain an increase in speed. This ability depends on the availability of an adjacent lane or the provision of an off-line bus stop. Where dual bus lanes or off-line bus stops are provided, the anticipated bus speed can be calculated using the distance between the bus stops served. Where congestion in the adjacent lane results in essentially no passing-lane availability, the buses will progress as if they were stopping at each stop with a zero dwell time at the intermediate stops. When partial use of the adjacent lane is available, the bus speed will be somewhere in between.

Equation 6-35 expresses the speed adjustment factor for skip-stop operation f_{sp} as a function of both the traffic in the adjacent lane and the buses in the curb lane (*21*). This factor reduces the faster base running time that results from the longer distances between stops used in the skip-stop pattern. If skip stops are not used, f_{sp} = 1.0 and the base running speed is based on the actual stop spacing. The volume v_{al} and capacity c_{al} of the adjacent lane are the same as those used previously for determining the facility capacity with skip-stop operation.

Equation 6-35

$$f_{sp} = 1 - \left(\frac{d_1}{d_2}\right)\left(\frac{v_{al}}{c_{al}}\right)^2\left(\frac{v_b}{B_{max}}\right)$$

where

f_{sp} = stop-pattern adjustment factor,

d_1 = distance for one-block stop pattern (ft or m),

d_2 = distance for multiple-block stop pattern (ft or m),

v_{al} = traffic volume in the adjacent lane (veh/h),

c_{al} = capacity of the adjacent lane (veh/h),

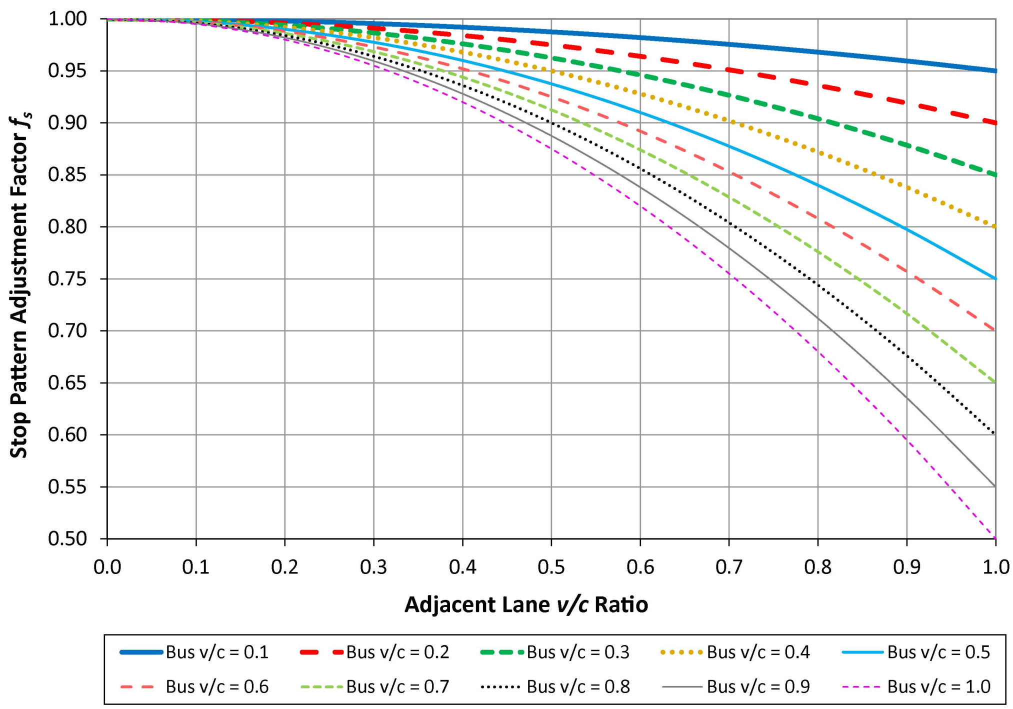
v_b = bus volume in the curb lane (bus/h), and

B_{max} = maximum bus capacity of the curb lane (bus/h).

Speed will need to be estimated separately for each skip-stop pattern. Maximum bus capacity should be based on a 25% failure rate.

Exhibit 6-74 illustrates values of the stop-pattern adjustment factor for a two-block stop pattern, for a range of bus lane and adjacent lane volume-to-capacity ratios. As bus volumes, adjacent lane volumes, or both increase, the stop-pattern adjustment factor value decreases, indicating a lower potential for bus speed improvements as a result of the skip-stop pattern. With no traffic in the adjacent lane (i.e., the adjacent lane *v/c* ratio is 0.0) and minimal bus volumes, the adjustment factor is 1.00, indicating that the two-block stop pattern results in a doubling of average bus speeds. When the adjacent lane is fully utilized, so that buses are unable to move into it (i.e., the adjacent lane *v/c* ratio is 1.0), and when the bus lane's maximum capacity is also fully utilized (i.e., the bus volume-to-capacity ratio is 1.0), the adjustment factor is 0.50, indicating that the skip-stop pattern has no effect on average bus speeds (2 × 0.5 = 1.0). Until the volume of adjacent lane reaches approximately half of its capacity (i.e., an adjacent lane *v/c* ratio of 0.5), the ability to achieve a two-fold increase in speed is not significantly reduced.

Exhibit 6-74
Illustrative Skip-Stop Speed Adjustment Factor Values



Source: Calculated.
Notes: Assumes two-block skip-stop pattern.
v/c = volume-to-capacity ratio.

STEP 6: ADJUST FOR BUS CONGESTION

Bus speeds within a bus lane along an arterial street decline as the lane becomes saturated with buses. This is because as the number of buses using the lane increases, there is a greater probability that one bus will delay another bus, either by using available loading areas or by requiring passing and weaving maneuvers. Simulation runs reported in *TCRP Report 26* (*21*) as well as observations of actual bus lane operations (*45*) show a sharp drop in bus speeds as bus volumes approach the bus lane's capacity. Exhibit 6-75 presents a bus–bus adjustment factor f_{bb} for speeds based on bus volumes relative to the bus lane capacity. These values were developed through simulation of Type 1 and Type 2 exclusive bus lanes, using an 80-s traffic signal cycle length, a g/C ratio of 0.5, 400-ft (125-m) block spacing, 20- to 50-s dwell times, and a 33% coefficient of dwell time variation.

Exhibit 6-75
Bus–Bus Interference Factor f_{bb} Values

Bus Volume-to-Capacity Ratio	Bus-Bus Interference Factor
<0.5	1.00
0.5	0.97
0.6	0.94
0.7	0.89
0.8	0.81
0.9	0.69
1.0	0.52
1.1	0.35

Source: *TCRP Report 26* (*21*).
Note: Bus lane capacity should be based on a 25% failure rate (i.e., maximum capacity).

Exhibit 6-10 illustrated the effects of increasing bus volumes on bus speeds. There is no effect on bus speeds until one-half of the bus lane's maximum bus capacity is in use. As scheduled bus volumes increase further, bus speeds begin to drop as buses interfere with the ability of each other to enter and exit bus stops and to pass. When a bus lane's maximum capacity is scheduled, achievable speeds are approximately half of what they could be at lower bus scheduled volumes. (As introduced in Section 5, Bus Capacity Methodology, the failure rate at maximum capacity is 25%, meaning that a bus has a one-in-four chance of being delayed at each bus stop it serves.)

STEP 7: DETERMINE AVERAGE SECTION SPEED

The base bus running time rate from Step 4 is divided by the skip-stop operation and bus–bus interference factors from Steps 5 and 6, respectively, to produce the overall section running time rate:

Equation 6-36

$$t_s = \frac{t_r}{f_{sp} f_{bb}}$$

where t_s is the section running time rate in minutes per mile or kilometer and all other variables are as previously defined. The section running time rate is then divided into 60 minutes per hour to obtain the section speed:

Equation 6-37

$$S_s = \frac{60}{t_s}$$

where S_s is the average section speed in miles or kilometers per hour.

STEP 8: DETERMINE AVERAGE FACILITY SPEED

The travel time rates for each section are multiplied by the respective section lengths and then summed to produce a total travel time for the facility:

$$t_{fac} = \sum_{i=1}^{N_{sec}} t_{s,i} L_i$$

Equation 6-38

where

- t_{fac} = facility travel time (min),
- N_{sec} = number of sections forming the facility,
- $t_{s,I}$ = section running time rate for section *i* (min/mi or min/km), and
- L_i = length of section *i* (mi or km).

Finally, the average facility speed is the facility length divided by the facility travel time, multiplied by 60 minutes per hour:

$$S_f = 60\left(\frac{L_{fac}}{t_{fac}}\right)$$

Equation 6-39

where S_f is the average facility speed (mi/h or km/h), L_{fac} is the facility length (mi or km), and t_{fac} is the facility travel time (min).

7. BUS RELIABILITY

This section presents the state of knowledge about factors that influence bus reliability. The impact of reliability issues on passenger quality of service was discussed in Chapter 4, Quality of Service Concepts.

Studies to date on bus reliability have been limited in scope, typically focusing on single transit routes or demonstrating a proof-of-concept using simulation. Comprehensive research is needed to quantify the effects of both external influences and scheduling and control strategies on bus reliability.

FACTORS INFLUENCING BUS RELIABILITY

Bus reliability is influenced by a number of factors, some under the control of transit operators and some not. These factors include:

- *Traffic conditions* (for on-street, mixed-traffic operations), including traffic congestion, traffic signal delays, parking maneuvers, incidents, etc.;
- *Road construction* and *right-of-way maintenance,* which create delays and may force a detour from the normal route;
- *Vehicle and maintenance quality*, which influence the probability that a vehicle will break down while in service;
- *Vehicle and staff availability*, reflecting whether there are sufficient vehicles available to operate the scheduled trips (some vehicles will be undergoing maintenance and others may be out of service for various reasons) and whether sufficient operators are available on a given day to operate those vehicles;
- *Transit preferential treatments* that partially offset traffic effects on transit operations;
- *Schedule achievability*, reflecting whether the route can be operated under usual traffic conditions and passenger loads, with sufficient layover time provided for operators and sufficient recovery time to allow most trips to depart on time even when they arrived at the end of the route late;
- *Evenness of passenger demand,* both between successive vehicles and from day to day for a given vehicle and run;
- *Differences in operator driving skills*, route familiarity, and adherence to the schedule—particularly in terms of early ("hot") running (*46*);
- *Wheelchair lift and ramp usage,* including the frequency of deployment and the amount of time required to secure wheelchairs;
- *Route length and the number of stops,* which increase a vehicle's exposure to events that may delay it—delays occurring earlier along a route result in longer overall trip times than similar delays occurring later along a route (*47, 48*); and
- *Operations control strategies* used to react to reliability problems as they develop, thus minimizing the impact of the problems (*49*).

The remainder of this section describes techniques for identifying and addressing bus reliability issues.

SCHEDULING AND HOLDING STRATEGIES

A Dutch study (*50*) investigated schedule- and headway-based holding strategies for short headway transit services. Schedule-based holding was found to be more effective than headway-based holding when no maximum holding time was applied. However, with a maximum holding time of 60 s, there was no difference in the effectiveness of the two holding strategies. The effects of vehicle holding on reliability and crowding were also studied; it was found that decreased irregularity due to holding can reduce crowding or enable smaller capacity slack.

Another study (*51*) modeled the operation of a hypothetical route to study optimal running time schedules. Using a performance measure that accounted for passengers' budgeted extra waiting time due to unreliable service and perceived waiting time for late buses, it was found that inserting slack into the schedule at timepoints rather than at the end of the route provided typical equivalent savings of 4.5 min/p of in-vehicle time, with the benefits increasing as the number of timepoints increased. Inserting slack at timepoints did not necessarily increase cycle time, because time spent holding at timepoints could be subtracted from recovery time at the end of the trip. The optimal scheduled route running time was found to be the mean time plus one standard deviation; the optimal route cycle time was found to be the mean plus two or three standard deviations.

A simulation study (*52*) focused on developing optimal bus schedules for taking advantage of TSP found that the best performance was achieved when an aggressive schedule was used (e.g., a majority of buses will be slightly behind schedule), in combination with conditional priority at signals that only grants priority to late buses and a strategy of holding early buses. Average running time, variability of running times and headways, and crowding were reduced with this strategy.

RELATIONSHIPS OF SERVICE CHARACTERISTICS TO RELIABILITY

A Seattle-area study based on AVL data (*53*) studied the impact of service characteristics on bus travel time variability. The most significant segment-level variable was lagged on-time deviation, or the bus already being late. Other significant variables that increased delay included use of high-floor buses, through-routing, presence of standees, severe weather, situations warranting a service alert, number of boarding passengers, and number of passengers onboard. These variables also had a significant negative effect at the route level. At the segment level, express buses and buses using managed lanes had a significant positive effect on decreasing delay.

A study in Beijing, China (*54*) developed estimates of reliability and their correlation to operational characteristics. A high correlation was found between service reliability and the characteristics of route length, headway, distance from the stop to the original terminal, and the provision of exclusive bus lanes. A Dutch study (*55*) also investigated the relationship between the length of a transit line and operational reliability and determined that splitting a line could result in improved reliability.

A study of transit lines in the Zurich region (*56*) considered onboard ticket sales as one factor in route variability. It was found that onboard ticket sales processes vary significantly and can be up to 20% of the total run time for the studied lines, which could significantly impact transit schedule reliability.

APPLICATIONS OF AVL DATA

TCRP Report 113 (*38*) provides information on designing a system to archive AVL data and to apply the collected data to various types of analyses that support a transit agency's operations, scheduling, and management functions. Examples in the report include the development of user-focused performance measures (described in more detail in TCQSM Chapter 5, Quality of Service Methodologies), analysis of short- and long-headway reliability problems, analysis of route travel-time variability, and the application of these analyses to improved route schedules. Several other studies (*57–59*) provide examples of the use of AVL data to support transit agency operations.

FORECASTING RELIABILITY

At the time of TCQSM publication, literature related to forecasting reliability focused on developing models for predicting transit vehicle arrival times for use with real-time information systems, based on archived AVL data (*54, 60*).

8. APPLICATIONS

This section presents examples of the types of real-world situations that this chapter's methods can be applied to.

ALTERNATIVE MODE, FACILITY, AND SERVICE COMPARISONS

The TCQSM bus analysis methods can be applied to a planning study or a formal alternatives analysis process to quickly compare the performance of different alternatives with each other. The information resulting from the analysis can then serve as inputs to ridership estimation, benefit-cost analysis, and alternative prioritization processes. Once one or more promising alternatives have been identified, simulation can be used if desired to confirm the alternative's operating performance. The general steps involved in this process are:

1. Specify the characteristics of each alternative to be compared, including mode, vehicle characteristics, facility type, and all other data needed to estimate the performance measures of interest using TCQSM methods.
2. If transit service already exists in the study corridor, perform a TCQSM analysis of its operating performance as a check on the reasonableness of the results. If necessary, revisit assumed or default input values used in the analysis that impact the performance results and calibrate them as needed to produce results that more closely match actual conditions.
3. Once default inputs have been calibrated, apply the TCQSM methods to each of the alternatives to estimate the performance measures of interest.

Changes in travel time can be used as an input to a ridership estimation process; for example, by applying elasticity factors from *TCRP Report 118: Bus Rapid Transit Practitioner's Guide* (*11*) for bus service. Travel times should be reflective of an average passenger's overall trip (including transfers) and not just of travel time in the corridor.

Speed can be used as an input for determining the number of transit vehicles required to operate service on the route(s) using the corridor, which then becomes an input for estimating operating and capital costs for the alternative. If TSP or bus lanes are part of the alternative, information from Chapter 3 can be used to estimate the change in running time variability associated with the alternative, which may reduce required schedule recovery time and route cycle time.

The capacity procedures can be used directly to develop assumptions about facility size (e.g., platform lengths at a BRT station) that will be required when developing a capital cost estimate for the alternative.

FARE COLLECTION TECHNOLOGY CHANGES

The dwell time calculation method provided in Step 4 of the bus capacity method can be used to evaluate the potential impacts of a change in fare collection technology. The steps involved in this process are as follows:

1. Conduct a study to determine current fare collection times. The process described in Appendix B for determining passenger service times can be followed. When multiple types of fare media are used (e.g., cash fares and

flash passes), the additional step of recording number of fares paid by media type will be required.

2. Compare the results to the TCQSM default values in Exhibit 6-4 to see where the results fall relative to the default value. In some cases—particularly with cash fares—the combination of bills and coins used to pay a fare drives the passenger service time. However, in other cases, vehicle characteristics (e.g., ease of boarding, ease of finding the fare collection device) or passenger characteristics also play a role.
3. Identify the passenger service time default value for the fare collection technology being considered. Consider whether the fare collection device will be retrofitted onto existing buses in addition to existing equipment (in which case, it may be in a less-convenient location that takes more time to access). Also consider the results of Step 2 and select an appropriate service value time value from the range of values given, if passengers appear to board faster or slower than suggested by the default value.
4. Calculate the change in passenger service time (up or down) that would result from the new technology. Combine with passenger count data (for example, from archived APC data) to estimate the change in dwell time along a given route.
5. Apply the TCQSM's speed estimation methodology to determine the resulting change in travel speed for a given route and from this, the change in route cycle time. Identify whether buses would need to be added to, or could be removed from a route, and the resulting operating costs or savings.

ASSESSING THE IMPACT OF TRANSIT PREFERENTIAL TREATMENTS

The information provided in Section 3 can be used in combination with TCQSM methods to evaluate the performance impact of particular treatments. In some cases—such as installing exclusive bus lanes—the treatment is directly accounted for in a TCQSM method. In other cases—for example, installing TSP—the base TCQSM method will need to be adjusted to account for the treatment's effects:

- The impact of TSP is best accounted for by adjusting the effective green time used in the g/C ratio by the average amount of time available to be added over the course of the hour. An HCM analysis will be needed to determine how much green time could be reallocated while meeting other constraints (e.g., intersection level of service standards, minimum pedestrian green time). Analyst judgment will be needed about whether the traffic signal timing and upstream bus stop location makes it more likely that a bus would use green extension or red truncation; this determines the maximum green time benefit a bus would receive. In addition, because of the need to keep intersections in coordination with other nearby intersections, priority is not likely to be granted every signal cycle, but rather every second or third cycle, and the added green time should be reduced proportionately. The TCQSM speed estimation method should then be run with and without TSP effects to estimate the resulting change in average bus speed due to TSP.
- Results of field studies of the effects of queue jumps on intersection bus delay are reported in Chapter 3. Analyst judgment should be applied in determining a

representative delay reduction value. This value should then be reduced to reflect the percentage of bus stops at traffic signals where queue jumps would be installed. (For example, if a 10% intersection delay reduction is determined to be reasonable, and queue jumps would be installed at half the signalized intersections along the facility where bus stops are located, use a 5% reduction to reflect the impact over the facility length.) The resulting value should then be used to reduce the base bus running time loss value from Exhibit 6-73 by the same percentage. Apply the TCQSM speed estimation method with and without TSP effects to estimate the resulting change in average bus speed due to queue jumps.

- Results of a field study (*33*) of the effect of curb extensions on corridor bus delay are reported in Chapter 3, indicating a 7% improvement in bus speeds when applied throughout a corridor. Multiply this value by the percentage of bus stops along the facility that will have this treatment. Apply the TCQSM speed estimation method normally and then increase the result by the calculated percentage.

DIAGNOSING AND TREATING CAPACITY ISSUES

In this application, archived AVL data are used to identify operational issues in the form of bus delays or overall slow running speeds in particular locations. *TCRP Report 113: Using Archived AVL-APC Data to Improve Transit Performance and Management* (*38*) provides guidance on how to do this. Once "hot spots" have been identified, TCQSM methods can then be used to evaluate the potential effectiveness of treatments at those locations (e.g., adding stop capacity, adding a transit preferential treatment).

SIZING BRT FACILITIES FOR A GIVEN DEMAND

If future demand for a BRT or other bus facility has already been estimated (for example, from a regional planning model), TCQSM methods can be used to develop to estimate the required size of stations along the facility, as well as identify any bus capacity constraints along the facility. The process involves these steps:

1. Assumptions will be needed about the vehicle type(s) that will use the facility, particularly the number of doors per vehicle and a design passenger load.
2. Assumptions about the types of service on the facility will also be needed—multiple-route operation such as in Pittsburgh, Ottawa, and Brisbane requires more attention to individual route demand characteristics than a single BRT route serving a facility that serves all stops.
3. Determine the number of vehicles required by route to serve the estimated hourly demand. For BRT service, use of a peak-hour factor is recommended (locally generated or a default of 0.75) to avoid overcrowded buses during peak 15-min conditions.
4. Determine the number of buses stopping at each station during the analysis hour.
5. Estimate the average dwell time based on passenger boarding and alighting demand at the station and assumptions about the fare payment method.

6. Apply the TCQSM to determine (*a*) the capacity of a single loading area, based on the dwell time determined above and then (*b*) the number of physical loading areas required to provide sufficient loading areas to serve the number of buses serving the station. If scheduled demand will be 70% or more of capacity, consider adding additional capacity (e.g., adding another loading area, implementing fare-paid platforms to reduce dwell times) to reduce bus interference effects that reduce bus speeds.
7. Repeat steps 4–6 as needed along the facility length.

The resulting station sizes can then be provided as inputs to a cost-estimation process.

9. CALCULATION EXAMPLE

THE SITUATION

Carroll City, the central city in a region of 750,000 people, is examining opportunities to improve transit service through its downtown core as part of a Downtown Circulation Plan. Existing bus service to downtown is concentrated on Carroll Street and George Street, a one-way couplet just over one mile in length. Both streets have two through lanes, with on-street parking provided on both sides of the street.

Calculation results have been updated as needed to reflect changes in the methodology or the example problem assumptions; these are not specifically marked as changes.

The couplet is served by six transit routes operated by Carroll City Transit (CCT), with combined peak-hour frequency of 26 buses per hour. Buses stop every block, with average block lengths of 660 ft. On-street parking is removed at bus stops to allow buses access to the curb, and buses must exit the traffic stream to serve passengers. Traffic signals are located at each intersection along the downtown couplet.

The city is considering two options for operational changes and two options for design changes to the Carroll Street/George Street couplet, with the intention of improving the quality of transit service in the downtown area:

Operational Options

1. Implement a "pay-on-exit" fare payment system. Outbound passengers from the CBD will pay their fare when exiting the bus.
2. Implement skip-stop operations, such that each route stops every other block. Each transit stop would serve three of the six downtown routes under this scenario.

Design Options

1. Install curb extensions (bus bulbs) at stops to allow buses to serve passengers without leaving the traffic stream. Note that this option also provides additional space for passenger amenities and reduces pedestrian crossing distance, changes that may also impact the facility's quality of service as well.
2. Remove on-street parking along one side of the street, narrow the existing two through lanes, and install a bus lane. Right turns will be allowed from the bus lane. Buses will be allowed to exit the bus lane and travel in the adjacent travel lane if needed (gaps in traffic permitting).

For the sake of this example, the design options are mutually exclusive, but in actual application, a pay-on-exit system could be implemented with either design option, and skip-stop operations could be implemented in tandem with a curbside bus lane.

THE QUESTION

What is the potential bus capacity in vehicles per hour, and what are the travel time impacts of the options described above (and their combinations) during the p.m. peak period?

BUS CAPACITY

Step 1. Define the Facility

Under both existing conditions and Design Options 1 and 2, the facility consists of the one-way couplet of Carroll Street and George Street through the downtown core.

Step 2. Gather Input Data

Bus Stop Demand Data

The following demand data associated with individual bus stops are required to conduct a capacity analysis. All data are for a defined hour (typically a peak hour).

- *Coefficient of variation of dwell times* (c_v) = 0.62, based on an analysis of CCT's archived AVL data.
- *Passenger demand peak-hour factor* (*PHF*) = 0.75, based on an analysis of CCT's archived APC data for the p.m. peak hour. Passenger boarding and alighting volumes are also available from the APC system.

Bus Stop Location Data

- All stops are *off-line*, as buses exit the travel lane to access the curb.
- All stops along the couplet are *far side*.
- Bus stop design is *linear*.
- Two *loading areas* (*N*) are provided at bus stops in the central portion of the couplet by removing additional on-street parking at the stop. This reflects the higher passenger demand at these stops. Other stops have only one loading area. See Exhibit 6-76 for stop-by-stop details.
- The downtown street network is a one-way grid, with signals on every block. Signals operate on 80-s cycles, with both streets at a given intersection receiving the same amount of green time. Accounting for traffic signal lost time, this results in a g/C ratio of 0.45 for buses on the couplet. The posted speed is 25 mi/h.
- *Curb travel lane traffic volume (v)* varies from 450 to 650 veh/h. See Exhibit 6-76 for stop-by-stop details.
- *Right-turning traffic volume* varies from 0 to 160 veh/h. See Exhibit 6-76 for stop-by-stop details.
- *Parallel pedestrian crossing volume* varies from 40 to 400 ped/h. See Exhibit 6-76 for stop-by-stop details.

Exhibit 6-76
Calculation Example: Summary of Existing Bus Stop Characteristics

	Carroll Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Number of loading areas	1	1	2	2	2	2	1	1
Curb-lane volume (veh/h)	450	500	500	550	600	650	600	600
Right-turn volume (veh/h)*	75	110	0	160	0	60	80	75
Pedestrian volume (ped/h)	40	70	140	120	280	400	120	80
	George Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Number of loading areas	1	1	2	2	2	2	1	1
Curb-lane volume (veh/h)	650	600	550	550	550	500	450	450
Right-turn volume (veh/h)*	80	120	60	0	160	0	90	130
Pedestrian volume (ped/h)	110	140	80	300	340	170	130	140

Note: *Included as part of the curb lane volume.

Step 3. Set a Design Bus Stop Failure Rate

The TCQSM recommends a design failure rate of 7.5 to 15% for downtown areas. Based on the policies of CCT and the Carroll City Public Works Department, 15% is selected as the design bus stop failure rate for the analysis.

Step 4: Determine Dwell Time

All bus routes operate using 40-ft low-floor buses that have a wide (two-channel) front door and a narrower (one-channel) rear door. Boarding occurs through the front door. Passengers purchasing single-ride or daily fares must use the farebox, but passengers with a monthly pass can bypass the farebox by showing their pass to the operator. Agency data show that approximately 55% of passengers use the heavily discounted monthly passes. Alighting passengers may use either door, but favor the rear door to avoid conflicts with boarding passengers. Standees are not normally present.

Three methods are given in Step 4 for determining dwell time: field measurements, default values, and calculation. When possible, field measurements are preferred; however, for the sake of example, the calculation method is illustrated below.

Exhibit 6-77 summarizes the average boardings and alightings per bus by stop.

Exhibit 6-77
Calculation Example: Average Boardings and Alightings per Bus by Stop

	Carroll Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Boarding passengers	3	5	10	5	12	8	3	6
Alighting passengers	3	2	7	8	7	3	0	0
	George Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Boarding passengers	2	4	8	10	6	12	4	3
Alighting passengers	2	4	6	6	8	4	2	0

Assign Boarding and Alighting Volume by Door Channel

The current boarding scenario reflects *double-channel* boarding, in which 45% of passengers use the farebox (channel 1) and the remaining 55% use the front door but bypass the farebox (channel 2).

No alighting passengers will use channel 1 (as it will be occupied by boarders using the farebox). Assume that 25% of alighting passengers exit from the front door via channel 2 (default value), with the remaining 75% of passengers using the rear door (channel 3).

Exhibit 6-78 shows the resulting average boarding and alighting volumes by door channel. Fractional numbers of people are used here, as these *average* volumes will be combined with average individual passenger service times to determine an overall average passenger service time by door channel. Rounding to whole passengers at this point would end up either over- or underestimating service times for a given combination of fare payment method and boarding direction, depending on which way the number was rounded, which would then result in the average dwell time being inaccurately estimated.

Exhibit 6-78
Calculation Example: Average Boardings and Alightings by Door Channel—Existing Conditions

	Door Channel	Carroll Street Bus Stops 1	2	3	4	5	6	7	8
Boardings	1	1.4	2.3	4.5	2.3	5.4	3.6	1.4	2.7
	2	1.7	2.8	5.5	2.8	6.6	4.4	1.7	3.3
	3	0	0	0	0	0	0	0	0
Alightings	1	0	0	0	0	0	0	0	0
	2	0.8	0.5	1.8	2.0	1.8	0.8	0	0
	3	2.3	1.5	5.3	6.0	5.3	2.3	0	0
	Door Channel	**George Street Bus Stops 1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Boardings	1	0.9	1.8	3.6	4.5	2.7	5.4	1.8	1.4
	2	1.1	2.2	4.4	5.5	3.3	6.6	2.2	1.7
	3	0	0	0	0	0	0	0	0
Alightings	1	0	0	0	0	0	0	0	0
	2	0.5	1.0	1.5	1.5	2.0	1.0	0.5	0
	3	1.5	3.0	4.5	4.5	6.0	3.0	1.5	0

Determine Average Passenger Service Time for Each Bus Door Channel

Exhibit 6-4 provides suggested default values for passenger service time based on the observed range. For the scenario under consideration, the following service times apply:

- Boardings through Channel 1: 4.5 s (exact change into farebox)
- Boardings through Channel 2: 2.0 s (visual fare inspection)
- Alightings through Channel 2: 2.5 s (front door)
- Alightings through Channel 3: 1.75 s (rear door)

In addition, when minor-direction flow through a door channel is more than 25% of the total flow through the door channel, boarding and alighting times should be increased by 20% to account for the congestion at the door. Two-directional flows occur in door channel 2, and minor-direction flow is more than 25% of the total flow at stops 1 and 4 on Carroll Street and at stops 1, 2, 3, and 5 on George Street.

Determine Passenger Flow Time for Each Bus Door Channel

Using Equation 6-4, calculate the average passenger flow time for each door channel. The calculations are shown in their entirety for Stop #1 on Carroll Street below.

$$t_{pf,i} = P_{a,i}t_{a,i} + P_{b,i}t_{b,i}$$

$$t_{pf,1} = 0 + (1.4)(4.5) = 6 \text{ s (rounded)}$$

$$t_{pf,2} = (0.8)(2.5 \times 1.2) + (1.7)(1.75 \times 1.2) = 6 \text{ s}$$

$$t_{pf,3} = (2.3)(1.75) + 0 = 4 \text{ s}$$

Exhibit 6-79 shows the average passenger flow time for each door channel resulting from the calculations.

Exhibit 6-79
Calculation Example: Average Passenger Flow Time by Door Channel (s)—Existing Conditions

	Carroll Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Channel 1 ($t_{pf,1}$)	6	10	20	10	24	16	6	12
Channel 2 ($t_{pf,2}$)	6	7	15	13	18	11	3	7
Channel 3 ($t_{pf,3}$)	4	3	9	11	9	4	0	0
Maximum ($t_{pf,max}$)	6	10	20	13	24	16	6	12
	George Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Channel 1 ($t_{pf,1}$)	4	8	16	20	12	24	8	6
Channel 2 ($t_{pf,2}$)	4	8	15	15	14	16	6	3
Channel 3 ($t_{pf,3}$)	3	5	8	8	11	5	3	0
Maximum ($t_{pf,max}$)	4	8	16	20	14	24	8	6

Determine the Boarding Lost Time

Stops 1, 2, 7, and 8 on both Carroll Street and George Street have only one loading area each, and therefore have no boarding lost time.

Assume that boarding lost time is equal to 2 s for the remaining stops, each of which have two loading areas. While there is no research specific to boarding lost time at stops with two loading areas, it is assumed that it would be less than the average boarding lost time of 4–4.5 s for stops with three loading areas.

Calculate the Dwell Time

Using Equation 6-5, calculate the average dwell time for each bus stop. The calculation is shown for Stop #1 on Carroll Street below, using an assumed door opening and closing time t_{oc} of 4 s.

$$t_d = t_{pf,max} + t_{oc} + t_{bl}$$

$$t_d = 6 + 4 + 0 = 10 \text{ s}$$

Exhibit 6-80 shows the average dwell time for each of the study facility stops.

Exhibit 6-80
Calculation Example: Average Dwell Time by Stop (s)—Existing Conditions

	Bus Stop							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Carroll Street	10	14	26	19	30	22	10	16
George Street	8	12	22	26	20	30	12	10

Step 5: Determine Loading Area Capacity

Determine the Clearance Time

Because the stops on the corridor are off-line, the clearance time is equal to 10 s (the minimum time for a standard bus to start up and travel its own length, and for the next bus to pull in) plus reentry delay. The calculation of reentry delay varies depending on the bus stop location relative to traffic signals; since all bus stops in the corridor are located at signalized intersections, Case 2 applies to all stops.

The first step is to determine the queue service time g_s, which represents time that buses are unable to leave the bus stop because a platoon of vehicles is discharging from the upstream traffic signal. Equation 6-9 through Equation 6-11 are used to determine this time. This process is illustrated for Stop #1 on Carroll Street, using a value of 1,625 veh/h for the saturation flow rate s_f, from Exhibit 6-60:

$$g_s = \frac{Q_r}{(s_f/3{,}600) - q_g} = \frac{q(C-g)}{(s_f/3{,}600) - q} = \frac{(v/3{,}600)(C-g)}{(s_f/3{,}600) - (v/3{,}600)}$$

$$g_s = \frac{(450/3{,}600)(80 - (0.45)(80))}{(1{,}625/3{,}600) - (450/3{,}600)}$$

$$g_s = 16.9\ s$$

The queue service time g_s is then compared to the effective green time g (equal to $g/C \times C$) and the smaller value is used as the queue service delay d_{qs}, per Equation 6-12. Since 16.9 s is smaller than (0.45 × 80 = 36 s), it is used as the queue service delay.

Next, the average delay that a bus experiences waiting for a gap in traffic is calculated, for the times that a platoon is not passing by the bus stop. The volume of traffic conflicting with bus movements during these times is given by Equation 6-13. For Stop #1 on Carroll Street, $v_{adj} = v(g/C) = 450\ \ 0.45\ \ = 203$ veh/h. This adjusted volume is then used in for Case 2 $c_{re,2}$. Assuming default values of 7.0 s and 3.3 s for critical headway and follow-up time, respectively, $c_{re,2}$ is calculated as follows for Stop #1 on Carroll Street:

$$c_{re,2} = v_{adj}\frac{e^{-vt_{ch}/3{,}600}}{1 - e^{-vt_f/3{,}600}}$$

$$c_{re,2} = 203\frac{e^{-(203)(7.0)/3{,}600}}{1 - e^{-(203)(3.3)/3{,}600}}$$

$$c_{re,2} = 804\ veh/h$$

Equation 6-7 is then used to calculate the average delay waiting for a gap in traffic before a bus can exit the bus stop:

$$d_{re,2} = \frac{3{,}600}{c_{re,2}} + 900\left[\frac{N_{la}}{c_{re,2}} - 1 + \sqrt{\left(\frac{N_{la}}{c_{re,2}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{re,2}}\right)\left(\frac{N_{la}}{c_{re,2}}\right)}{450}}\right] - 3.3$$

$$\mathrm{d_{re,2}} = \frac{3{,}600}{804} + 900\left[\frac{1}{804} - 1 + \sqrt{\left(\frac{1}{804} - 1\right)^2 + \frac{\left(\frac{3{,}600}{804}\right)\left(\frac{1}{804}\right)}{450}}\right] - 3.3$$

$$\mathrm{d_{re,2}} = 1.2\ \mathrm{s}$$

Because all stops are far-side stops, Equation 6-15 is used to calculate the reentry delay. This value is the average of the queue service delay and the gap-in-traffic delay, weighted by the proportion of time a platoon of vehicles is and is not present, respectively. For Stop #1 on Carroll Street, the calculations are as follows:

$$d_{re,2fs} = d_{qs}\frac{d_{qs}}{C} + d_{gt}\frac{(C - d_{qs})}{C}$$

$$d_{re,2fs} = 16.9\frac{16.9}{80} + 1.2\frac{(80 - 16.9)}{80}$$

$$d_{re,2fs} = 4.5\ s$$

Finally, the clearance time t_c is the reentry delay (4.5 s) plus the minimum bus start-up and movement time (10 s), or 14.5 s. Exhibit 6-81 provides reentry and clearance times for all stops in the corridor.

Exhibit 6-81
Calculation Example: Reentry and Clearance Times by Stop (s)—Existing Conditions

	Carroll Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Reentry time t_{re} (s)	5	6	6	7	9	12	9	9
Clearance time t_c (s)	15	16	16	17	19	22	19	19
	George Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Reentry time t_{re} (s)	12	10	8	8	8	6	5	5
Clearance time t_c (s)	22	20	18	18	18	16	15	15

Calculate the Loading Area Capacity

Use Equation 6-6 to calculate the loading area capacity for each stop. Using Exhibit 6-56, the standard normal variable Z associated with the design failure rate of 15% is 1.04. The calculation of loading area capacity for Stop #1 on Carroll Street is shown below.

$$B_l = \frac{3{,}600(g/C)}{t_c + t_d(g/C) + t_{om}} = \frac{3{,}600(g/C)}{t_c + t_d(g/C) + Zc_v t_d}$$

$$B_l = \frac{3{,}600(0.45)}{14.5 + 10(0.45) + (1.04)(0.60)(10)}$$

$$B_l = \frac{1{,}620}{25.24} = 64\ \text{bus/h}$$

Exhibit 6-82 shows the loading area capacity for each stop.

Exhibit 6-82
Calculation Example: Loading Area Capacity by Stop (bus/h)—Existing Conditions

	Bus Stop							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Carroll Street	64	53	37	48	31	36	54	44
George Street	53	50	40	36	42	34	59	64

Step 6: Determine Bus Stop Capacity

Determine the Number of Effective Loading Areas

Use Exhibit 6-63 to estimate the number of effective loading areas N_{el} at each stop. Stops with one loading area will 1.00 effective loading areas, while stops with two loading areas will have 1.85 effective loading areas (as the stops are off-line).

Adjust Capacity for Traffic Blockage

Use Equation 6-17 to calculate the traffic blockage adjustment factor f_{tb}. The bus stop location factor f_l is 0.5 because stops are located far side and buses are able to move into the adjacent travel lane as needed.

The capacity of the curb lane through movement c_{th} is estimated as 1,625 × (g/C), or 731, based on the saturation flow values in Exhibit 6-60. The capacity of the right-turn movement c_{rt} is estimated as 1,450 × (g/C) × (1-(pedestrian volume/2,000)), using the equation accompanying Exhibit 6-65. For Stop #1 on Carroll Street, c_{rt} equals 639 veh/h. The curb lane capacity is the volume-weighted average of the through and right-turn capacities:

$$c_{cl} = 731\frac{(450-75)}{450} + 639\frac{75}{450} = 716 \text{ veh/h}$$

The traffic blockage adjustment factor calculation for Stop #1 on Carroll Street is as follows:

$$f_{tb} = 1 - f_l\left(\frac{v_{cl}}{c_{cl}}\right)$$

$$f_{tb} = 1 - 0.5\left(\frac{450}{723}\right) = 0.69$$

Exhibit 6-83 shows the traffic blockage adjustment factor for each stop.

Calculate Bus Stop Capacity

Use Equation 6-18 to calculate the bus stop capacity, rounding down the result to the nearest whole number. The calculation for Stop #1 on Carroll Street is shown below.

$$B_s = N_{el}B_l f_{tb} = (1.0)(64)(0.69) = 44 \text{ bus/h}$$

Exhibit 6-83 shows the bus stop capacity for each stop on the facility.

Exhibit 6-83
Calculation Example: Bus Stop Capacity—Existing Conditions

	Carroll Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Loading area capacity B_l (bus/h)	64	53	37	48	31	36	54	44
Effective loading areas N_{el}	1.00	1.00	1.85	1.85	1.85	1.85	1.00	1.00
Blockage factor f_{tb}	0.69	0.65	0.66	0.61	0.59	0.54	0.58	0.58
Bus stop capacity B_s	44	33	44	53	34	35	31	25
	George Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Loading area capacity B_l (bus/h)	53	50	40	36	42	34	59	64
Effective loading areas N_{el}	1.00	1.00	1.85	1.85	1.85	1.85	1.00	1.00
Blockage factor f_{tb}	0.55	0.58	0.62	0.62	0.59	0.66	0.68	0.68
Bus stop capacity B_s	29	28	45	41	45	41	40	43

Step 7: Determine Facility Bus Capacity

As skip-stop operations are not used on this facility, the facility bus capacity is simply equal to the capacity of the critical bus stop (i.e., the bus stop with the lowest capacity). The critical bus stop on Carroll Street is Stop #8, with a capacity of 25 buses per hour, and the critical bus stop on George Street is Stop #2, with a capacity of 28 buses per hour. Because 26 buses are currently scheduled in the peak hour in each direction, the result of 25 buses per hour for the design capacity on Carroll Street indicates that the desired 15% failure rate cannot be achieved and that buses will experience less reliable operations than planned.

BUS SPEED

Step 1: Define the Facility

Under the existing conditions and Design Options 1 and 2, the facility consists of the one-way couplet of Carroll Street and George Street through the downtown core.

Step 2: Gather Input Data

The input data needed to calculate bus speed are largely available from the bus capacity analysis described above. In addition, the following input data are required:

- Average stop spacing is eight stops per mile in each direction.
- There are 26 buses per hour scheduled at the critical bus stop in each direction.
- Traffic signals are located every block (approximately 8 signals per mile). The signals are not timed specifically for bus operations.

Step 3: Determine Maximum Capacity

Maximum capacity is determined by recalculating the capacity of the critical stop in each direction using a 25% failure rate, instead of the 15% used previously to determine design capacity. The critical bus stop on Carroll Street was Stop #8, and its maximum capacity is 28 buses per hour. The critical stop on George Street was Stop #2, and its maximum capacity is 30 buses per hour. The scheduled number of buses (26 per hour) is less than the maximum capacity in both directions.

Step 4: Determine Base Bus Running Time

Calculate the Unimpeded Bus Running Time Rate

Because the conditions in the study area (typical signal timing, posted speed of 25 mi/h) match those used to develop Exhibit 6-70, the exhibit can be used directly to estimate bus speeds. Using the results of the dwell time calculations given previously (Exhibit 6-80), it is determined that the average dwell time of all stops is 18.4 s on Carroll Street and 17.5 s for George Street. From Exhibit 6-70, the unimpeded bus running time rates for 10- and 20-s dwell times are 5.06 min/mi and 6.39 min/mi, respectively. Interpolating between these values for dwell times of 18.4 and 17.5 s gives unimpeded bus running time rates of 6.18 and 6.06 min/mi for Carroll Street and George Street, respectively.

These running time rates could also be calculated directly using Equation 6-27 through Equation 6-33. The time spent decelerating from running speed to a stop, assuming a standard bus deceleration rate of 4.0 ft/s^2, is given by Equation 6-28:

$$t_{dec} = \frac{c_f v_{run}}{a} = \frac{(1.47)(25)}{(4)} = 9.2\ s$$

Similarly, the time spent accelerating back to running speed from a stop, assuming an average standard bus acceleration rate of 3.4 ft/s^2 to 25 mi/h, is calculated from Equation 6-27:

$$t_{acc} = \frac{c_f v_{run}}{d} = \frac{(1.47)(25)}{(3.4)} = 10.8\ s$$

As this is not a busway operation, the time t_{sta} and distance L_{sta} spent by express buses passing through stations at a reduced speed are set to zero. The total distance travelled per stop while accelerating or decelerating is given by Equation 6-30:

$$L_{ad} = 0.5at_{acc}^2 + 0.5dt_{dec}^2 + L_{sta}$$

$$L_{ad} = (0.5)(3.4)(10.8)^2 + (0.5)(4.0)(9.2)^2 + 0$$

$$L_{ad} = 368\ ft$$

The total distance travelled at running speed per mile or kilometer is the length of a mile (5,280 ft) minus the product of the number of stops per mile and the acceleration/deceleration distance per stop, as given by Equation 6-31:

$$L_{rs} = L_{mk} - N_s L_{ad} = 5{,}280 - (8)(368) = 2{,}336\ ft$$

Because this result is greater than zero, buses can reach the assumed running speed between stops and no adjustment to the assuming running speed is required.

The time spent travelling at running speed in each mile is the distance travelled at running speed divided by the running speed (converted from mi/h to ft/s), as given by Equation 6-32:

$$t_{rs} = \frac{L_{rs}}{c_f v_{run}} = \frac{2{,}336}{(1.47)(25)} = 63.6\ s$$

Finally, the unimpeded running time rate is the sum of the time spent at running speed plus the sum of the average dwell time and acceleration and deceleration times associated with each bus stop, as calculated by Equation 6-33. For Carroll Street:

$$t_u = \frac{t_{rs} + N_s(t_{dt} + t_{acc} + t_{dec} + t_{sta})}{60}$$

$$t_u = \frac{63.6 + 8(18.4 + 10.8 + 9.2 + 0)}{60}$$

$$t_u = 6.18\ min/mi$$

Similarly, the unimpeded running time rate for George Street is calculated as 6.06 min/mi. These values match those obtained using Exhibit 6-70.

Calculate Additional Running Time Losses

Exhibit 6-73 is used to determine the base bus running time loss t_l, representing delay due to traffic signals and traffic interference. Both Carroll Street and George Street are mixed-traffic facilities in the CBD with typical signal operations; Exhibit 6-73 gives a value of 3.0 min/mi for t_l under these conditions.

Calculate the Base Bus Running Time Rate

Equation 6-34 is used to calculate the base bus running time, which is simply the sum of the unimpeded running time rate t_u and the additional running time losses t_l. The base bus running time is 9.18 min/mi for Carroll Street and 9.06 min/mi for George Street.

Step 5: Adjust for Skip-Stop Operations

As skip-stop operations are not being used under existing conditions, no adjustment needs to be made (i.e., $f_{sp} = 1$).

Step 6: Adjust for Bus Congestion

The bus volume-to-capacity ratio is determined by dividing the scheduled number of buses per hour (26) on each street by the street's maximum capacity, calculated earlier in Step 3 (28 and 30 bus/h for Carroll and George Street, respectively). The results are bus v/c ratios of 0.93 and 0.87 for Carroll and George Streets, respectively.

These v/c ratios are then used as inputs in Exhibit 6-75 to determine Interpolating from the exhibit gives factors of 0.64 and 0.73 for Carroll and George Streets, respectively.

Step 7: Determine Average Section Speed

Equation 6-36 and Equation 6-37 are used to calculate the section running time rate t_s and speed S_s. For Carroll Street:

$$t_s = \frac{t_r}{f_{sp} f_{bb}} = \frac{9.18}{(1)(0.64)} = 14.34\ min/mi$$

$$S_s = \frac{60}{t_s} = \frac{60}{14.34} = 4.2 \text{ mi/h}$$

Similarly, for George Street:

$$t_s = \frac{t_r}{f_{sp} f_{bb}} = \frac{9.06}{(1)(0.76)} = 11.92\ min/mi$$

$$S_s = \frac{60}{t_s} = \frac{60}{11.92} = 4.8 \text{ mi/h}$$

OPTIONS ASSESSMENT

As described in the introduction to this example, there are several operations and design options under consideration to improve bus service through the downtown core. The capacity and speed effects of each option are evaluated here in more detail. It is assumed that other considerations (e.g., potential drainage issues associated with curb extensions, potential increase in walking distances to bus stops with skip stops) have already been evaluated and the options determined to be feasible, or that these considerations will be evaluated at a later stage of the evaluation.

For each option, calculations are shown only for the portions of the capacity and speed methodologies that change with each option (e.g., the change to a fare-free zone affects only the dwell time calculations). In addition, the effect of each option on overall capacity and speed is discussed.

Operations Option 1: Implement Pay-on-Exit

Under Operations Option 1, CCT would implement a "pay-on-exit" fare payment system. Passengers boarding in the CBD could use any door and would pay their fare on exiting the bus. (Inbound passengers to the CBD would pay their fare on boarding, as usual). One hoped-for outcome of such a change would be to reduce dwell times at the busy CBD stops by allowing passengers to board more quickly.

Operations Option 1 directly affects only Step 4, Determine Dwell Times, of the bus capacity methodology, and does not directly impact the procedures for bus speed at all (although the change in average dwell time will of course require that bus speeds be recalculated). The impacts on dwell time are described below.

Capacity Step 4: Determine Dwell Times

Assign Boarding and Alighting Volume by Door Channel

The change to a fare-free zone would result in all-door boarding along the facility. Passengers would have the option of boarding through the rear door, resulting in three door channels.

Using Exhibit 6-58, assign 45% of boarding passengers to the busiest door channel and 45% of alighting passengers to the busiest door channel. To be conservative, assume that the busiest door channel for boarding passengers is that same as that for alighting passengers.

Exhibit 6-84 shows the resulting boarding and alighting volumes by door channel.

Exhibit 6-84
Calculation Example: Average Boardings and Alightings by Door Channel (s)—Pay-on-Exit

	Door Channel	Carroll Street Bus Stops 1	2	3	4	5	6	7	8
Boardings	1	1.4	2.3	4.5	2.3	5.4	3.6	1.4	2.7
	2	0.8	1.4	2.8	1.4	3.3	2.2	0.8	1.7
	3	0.8	1.4	2.8	1.4	3.3	2.2	0.8	1.7
Alightings	1	0	0	0	0	0	0	0	0
	2	0.8	0.5	1.8	2.0	1.8	0.8	0	0
	3	2.3	1.5	5.3	6.0	5.3	2.3	0	0
	Door Channel	**George Street Bus Stops 1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Boardings	1	0.9	1.8	3.6	4.5	2.7	5.4	1.8	1.4
	2	0.6	1.1	2.2	2.8	1.7	3.3	1.1	0.8
	3	0.6	1.1	2.2	2.8	1.7	3.3	1.1	0.8
Alightings	1	0	0	0	0	0	0	0	0
	2	0.5	1.0	1.5	1.5	2.0	1.0	0.5	0
	3	1.5	3.0	4.5	4.5	6.0	3.0	1.5	0

Determine Average Passenger Service Time for Each Bus Door Channel

Exhibit 6-4 provides suggested default values for passenger service time based on the observed range. For the all-door boarding, the following service times apply:

- Boardings: 1.75 s,
- Alightings through Channels 1 and 2: 2.5 s (front door), and
- Alightings through Channel 3: 1.75 s (rear door).

As before, passenger service times are increased by 20% for door channels where the minor flow is more than 25% of the total passenger flow through the door.

Determine Average Passenger Flow Time for Each Bus Door Channel

Equation 6-4 is used to calculate the passenger flow time for each door channel. Exhibit 6-85 shows the passenger flow time for each door channel resulting from the calculations.

Exhibit 6-85 Calculation Example: Average Passenger Flow Time by Door Channel (s)—Pay-on-Exit

	Carroll Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Channel 1 ($t_{pf,1}$)	2	4	8	4	10	6	2	5
Channel 2 ($t_{pf,2}$)	4	4	11	9	12	7	1	3
Channel 3 ($t_{pf,3}$)	7	6	17	16	18	9	1	3
Maximum ($t_{pf,max}$)	7	6	17	16	18	9	2	5
	George Street Bus Stops							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Channel 1 ($t_{pf,1}$)	2	3	6	8	5	10	3	2
Channel 2 ($t_{pf,2}$)	3	5	9	10	10	8	4	1
Channel 3 ($t_{pf,3}$)	5	9	15	12	20	11	5	3
Maximum ($t_{pf,max}$)	5	9	15	12	20	11	5	3

Comparing Exhibit 6-85 to Exhibit 6-79, passenger service times increased by 1 s at three stops, and by 3 s and 6 s at one stop each. Service times decreased at the other eleven stops, with reductions ranging from 1 s to 13 s. Overall, service times are reduced by an average of 3 s per stop, and the longest service times on both streets are both reduced. The variable effect is due to the different mixtures of boarding and alighting passengers at each stop; stops with higher boarding volumes will benefit most from the change, while stops with more alightings than boardings may actually experience increased passenger boarding time due to the increased passenger congestion at the doors.

As a result, the impact on bus capacity and speed resulting from a switch to a pay-on-exit system will depend heavily on the mix of boarding and alighting passengers at the critical bus stop along the facility.

Determine the Boarding Lost Time

Boarding lost time does not change with all-door boarding.

Calculate the Dwell Time

Equation 6-5 is used to calculate the average dwell time for each bus stop, using the same average door opening and closing time (4 s) as before. Exhibit 6-86 shows the average dwell time for each of the study facility stops.

Exhibit 6-86
Calculation Example: Average Dwell Time by Stop (s)—Pay-on-Exit

	Bus Stop							
	1	2	3	4	5	6	7	8
Carroll Street	10	10	23	21	24	15	6	9
George Street	9	13	21	18	26	17	9	7

Assessment of Capacity and Speed Impacts

Exhibit 6-87 shows the bus capacity and speed impacts results associated with Operations Option 1. This exhibit shows mixed results for the operational impacts of the pay-on-exit system, with a moderate increase in capacity and speed for Carroll Street, but a small reduction in capacity and no change in speed on George Street. The lack of improvement on George Street is a result of the pay-on-exit system resulting in a small increase in dwell time at the critical stop (Stop #2). In this case, the critical stop was not the stop with the longest dwell time, but the stop with the longest dwell time among the four stops with only one loading area.

Exhibit 6-87
Calculation Example: Summary of Impacts—Pay-on-Exit

	Existing Conditions		Operations Option 1			
	Capacity (bus/h)	Speed (mi/h)	Capacity (bus/h)	Speed (mi/h)	% Change in Speed	Minutes Saved per Bus
Carroll Street	25	4.2	32	5.8	+38%	4.0
George Street	28	4.8	27	4.8	+0%	0.0

Operations Option 2: Implement Skip-Stop Operations

The option under consideration would have buses stop every other stop, resulting in a two-stop skip pattern.

Capacity Step 4: Determine Dwell Time

Because each bus is stopping half as frequently as it used to, dwell times at the remaining stops will be twice as high as before, assuming no loss of ridership due to the longer walking distances to stops for some passengers.

Capacity Step 7: Determine Bus Facility Capacity

Use Equation 6-21 to calculate the adjacent lane impedance factor f_i. Use an average volume of 550 veh/h for both Carroll Street and George Street for the adjacent lane volume based on the information shown in Exhibit 6-76.

$$f_i = 1 - 0.8\left(\frac{v_a}{c_a}\right)^3 = 1 - 0.8\left(\frac{550}{731}\right)^3 = 0.66$$

Use Equation 6-20 to calculate the capacity adjustment factor f_k. Assume that scheduled bus arrivals will be spread out throughout the peak hour, but that actual bus arrivals will deviate somewhat from the schedule (but not excessively), and set f_a = 0.75.

$$f_k = \frac{1 + f_a f_i (N_{ss} - 1)}{N_{ss}} = \frac{1 + (0.75)(0.66)(2-1)}{2} = 0.75$$

Determine the individual capacity of the two bus stops (B_1 and B_2) using the individual bus stop capacity results shown in Exhibit 6-83. Assume that B_1 consists of stops 1, 3, 5, and 7, and that B_2 consists of stops 2, 4 , 6, and 8. Exhibit 6-88 shows the bus stop group capacities.

Exhibit 6-88
Calculation Example: Bus Stop Group Capacities (bus/h)—Skip Stops

		Bus Stop 1/2	3/4	5/6	7/8	Minimum
Carroll Street	B_1	35	28	22	29	22
	B_2	26	40	26	21	21
George Street	B_1	22	28	29	27	22
	B_2	20	25	24	30	20

Use Equation 6-19 to calculate design bus facility capacity:

$$Carroll\ Street: B = f_k(B_1 + B_2) = (0.75)(22 + 21) = 32 \text{ bus/h}$$

$$George\ Street: B = f_k(B_1 + B_2) = (0.75)(22 + 20) = 31 \text{ bus/h}$$

Speed Step 4: Determine Base Bus Running Time Rate

With a two-stop skip-stop pattern, each bus will stop at half as many stops as it did before. As a result, the bus stop spacing within each pattern is reduced from 8 stops/mi to 4 stops/mi and the average dwell time increases to 36.8 and 35.0 s for Carroll and George Streets, respectively. Therefore, the base bus running time rate needs to be recalculated. Interpolating from Exhibit 6-70, the new unimpeded bus running times are 5.51 and 5.39 min/mi for Carroll Street and George Street, respectively. The running time losses remain the same at 3 min/mi for both streets, resulting in base bus running time rates of 8.51 and 8.39 min/mi for Carroll and George Streets, respectively.

Speed Step 5: Adjust for Skip-Stop Operations

Use Equation 6-35 to calculate the stop pattern adjustment factor f_{sp} for each stop group. This factor reflects how The calculation for stop group 1 on Carroll Street is shown below. The values for d_1 and d_2 are 660 feet and 1,320 feet, respectively, based on 8 total stops per mile and 2 stop groups. Assume that the routes are split such that half of the total number of buses scheduled per hour use each group.

Maximum bus facility capacity will also need to be determined by recalculating bus facility capacity using a 25% failure rate. These capacities are 38 and 35 bus/h for Carroll and George Street, respectively.

The calculation of the stop pattern adjustment factor is shown for Carroll Street:

$$f_{sp} = 1 - \left(\frac{d_1}{d_2}\right)\left(\frac{v_{al}}{c_{al}}\right)^2\left(\frac{v_b}{B_{max}}\right)$$

$$f_{sp} = 1 - \left(\frac{660}{1{,}320}\right)\left(\frac{550}{731}\right)^2\left(\frac{26}{38}\right)$$

$$f_{sp} = 1 - (0.5)(0.75)^2(0.68)$$

$$f_{sp} = 0.81$$

Similarly, the stop pattern adjustment factor is 0.79 for George Street.

Speed Step 6: Adjust for Bus Congestion

Skip-stop operations increase a bus facility's maximum capacity and thereby reduce bus-bus interference. On Carroll Street, the bus volume-to-capacity ratio is (26 / 38) or 0.68; the corresponding bus–bus interference factor from Exhibit 6-75 is 0.90. For

George Street, the bus volume-to-capacity ratio is 0.74 and the corresponding bus–bus interference factor is 0.86.

Assessment of Capacity and Speed Impacts

Exhibit 6-89 shows the bus capacity and speed impacts results associated with implementing a two-block skip-stop pattern on Carroll Street and George Street. This exhibit shows moderate improvements in bus speeds on the two streets associated with the conversion to skip-stop operations. Even though dwell times increased at the remaining stops served by each bus, the reduction in the number of stops made by a given bus resulted in a net positive speed benefit. However, this benefit need to be weighed against a potential decrease in pedestrian access to buses associated with the longer stop spacing. Although the maximum additional walk for passengers is one block and downtown areas typically have good sidewalk networks, those passengers who would need to walk an extra block (660 ft, approximately 3 min) would experience a longer overall trip.

Exhibit 6-89
Calculation Example: Summary of Impacts—Skip Stops

	Existing Conditions		Operations Option 2			
	Capacity (bus/h)	Speed (mi/h)	Capacity (bus/h)	Speed (mi/h)	% Change in Speed	Minutes Saved per Bus
Carroll Street	25	4.2	38	5.1	+21%	2.5
George Street	28	4.8	35	5.8	+21%	2.2

Design Option 1: Install Curb Extensions

Installing curb extensions reduces the clearance time for buses when leaving stops by eliminating the reentry delay component of clearance time (i.e., the stops will be converted from off-line to on-line stops).

Step 5: Determine Loading Area Capacity

Exhibit 6-81 shows the clearance time associated with off-line stops under existing conditions. With on-line stops, the clearance time would be equal to 10 s for every stop, as reentry delay would be eliminated. The calculation for Stop 1 on Carroll Street is shown below.

$$B_l = \frac{3{,}600(g/C)}{t_c + t_d(g/C) + t_{om}} = \frac{3{,}600(g/C)}{t_c + t_d(g/C) + Zc_v t_d}$$

$$B_l = \frac{3{,}600(0.45)}{10 + 10(0.45) + (1.04)(0.60)(10)}$$

$$B_l = \frac{1{,}620}{20.74} = 78 \text{ bus/h}$$

Exhibit 6-90 shows the loading area capacity for each stop.

	Bus Stop							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Carroll Street	78	65	43	62	38	48	78	60
George Street	87	71	48	43	52	38	71	78

Exhibit 6-90
Calculation Example: Loading Area Capacity by Stop (bus/h): Design Option 1

The remainder of the bus capacity and speed procedures are performed as shown previously for existing conditions, with the exception that the number of effective loading areas should be recalculated using Exhibit 6-63 using the "on-line, random arrivals" column, resulting in the stops with two physical loading areas providing 1.75 effective loading areas.

Assessment of Capacity and Speed Impacts

Exhibit 6-91 shows the bus capacity and speed impacts results associated with Design Option 1, taking the average of the two bus groups for Carroll Street and George Street. This exhibit shows moderate improvements in bus speeds associated with the addition of curb extensions along the corridor.

	Existing Conditions		Design Option 1			
	Capacity (bus/h)	**Speed (mi/h)**	**Capacity (bus/h)**	**Speed (mi/h)**	**% Change in Speed**	**Minutes Saved per Bus**
Carroll Street	25	4.2	34	5.9	+40%	4.1
George Street	28	4.8	40	6.3	+31%	3.0

Exhibit 6-91
Calculation Example: Summary of Design Option 1 Impacts

Design Option 2: Implement Curbside Bus Lanes

The bus lanes being considered will allow other vehicles to enter the bus lane to make right turns at intersections and will allow buses to enter the adjacent lane as needed to move around other vehicles in the bus lane. Thus, these will be Type 2 bus lanes.

Capacity Step 5: Determine Loading Area Capacity

One of the parking lanes is being removed and the existing travel lanes are being narrowed to provide room for a curbside bus lane. Buses will stop in the bus lane at stops; thus, the stops will be on-line. The procedures for adjusting the loading area capacity to reflect on-line stops are described above for Design Option 1 and remain the same under Design Option 2.

Capacity Step 6: Determine Bus Stop Capacity

The capacity of the right-turn movement is calculated based on Exhibit 6-65. Exhibit 6-76 provides pedestrian volumes for each stop. The calculation is shown for Stop 1 on Carroll Street below:

$$c_{rt} = 1{,}450(g/C)\left\{1 - \frac{(\text{peds/h})}{2{,}000}\right\}$$

$$c_{rt} = 1{,}450(0.45)\left\{1 - \frac{40}{2{,}000}\right\} = 639 \text{ veh/h}$$

The capacity of the through movement c_{th} is 731 veh/h, as before. The curb lane capacity is the volume-weighted average of the through and right-turn capacities, with the through volume reflecting the scheduled number of buses and the right-turn volume reflecting the values given in Exhibit 6-76.

$$c_{cl} = 731\frac{(101-75)}{101} + 639\frac{75}{101} = 663 \text{ veh/h}$$

The traffic blockage adjustment factor calculation for Stop #1 on Carroll Street is as follows:

$$f_{tb} = 1 - f_l\left(\frac{v_{cl}}{c_{cl}}\right)$$

$$f_{tb} = 1 - 0.5\left(\frac{101}{663}\right) = 0.92$$

Exhibit 6-92 shows the right-turn capacity, curb lane capacity, and traffic blockage adjustment factor by stop.

Exhibit 6-92
Calculation Example: Traffic Blockage Factor f_l by Stop (veh/h)

	Carroll Street Bus Stops							
	1	2	3	4	5	6	7	8
Right-turn capacity, c_{rt} (veh/h)	639	630	607	613	561	522	613	626
Curb lane capacity, c_{cl} (veh/h)	663	649	731	630	731	585	642	653
Traffic blockage adjustment factor, f_{tb}	0.92	0.90	0.98	0.85	0.98	0.93	0.92	0.92
	George Street Bus Stops							
	1	2	3	4	5	6	7	8
Right-turn capacity, c_{rt} (veh/h)	617	607	626	555	542	597	610	607
Curb lane capacity, c_{cl} (veh/h)	645	629	658	731	568	731	637	628
Traffic blockage adjustment factor, f_{tb}	0.92	0.88	0.93	0.98	0.84	0.98	0.91	0.88

Speed Step 4: Determine Base Bus Running Time Rate

Exhibit 6-73 is used to determine the base bus running time loss t_l. For Type 2 bus lanes in the CBD with typical signal operations, t_l is 2.0 min/mi.

The steps involved with the remainder of the speed calculation remain the same as before.

Assessment of Capacity and Speed Impacts

Exhibit 6-93 shows the bus capacity and speed impacts results associated with Design Option 2. The bus lanes results in substantial improvements in speed and capacity.

Exhibit 6-93
Calculation Example: Summary of Design Option 2 Impacts, No Skip-Stop Operation

	Existing Conditions		Design Option 2			
	Capacity (bus/h)	Speed (mi/h)	Capacity (bus/h)	Speed (mi/h)	% Change in Speed	Minutes Saved per Bus
Carroll Street	25	4.2	55	7.3	+74%	6.1
George Street	28	4.8	62	7.4	+54%	4.4

COMMENTS

The design options used in this example focused on facilitywide improvements, for the sake of illustrating the TCQSM's bus speed and capacity calculation methods. In actual practice, an agency could also evaluate smaller-scale options focusing on improving conditions at the critical stop(s). Such an effort could produce reasonable benefits at a considerably lower implementation cost.

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APPENDIX A: EXHIBITS IN METRIC UNITS

Exhibit 6-7m
Estimated Average Bus Speeds on Grade-Separated Busways (km/h)

Average Stop Spacing (km)	Average Dwell Time (s) 0	15	30	45	60
80 km/h RUNNING SPEED					
1.0	54	42	36	31	28
1.5	61	50	44	39	35
2.0	65	55	49	45	41
3.0	69	61	57	53	49
4.0	71	65	61	57	54
90 km/h RUNNING SPEED					
1.0	57	43	36	32	28
1.5	65	52	45	40	36
2.0	70	58	52	47	43
3.0	75	66	61	56	52
4.0	79	71	66	61	58
100 km/h RUNNING SPEED					
1.0	59	43	37	32	28
1.5	68	53	47	41	37
2.0	74	61	54	48	44
3.0	81	70	63	58	54
4.0	85	75	70	65	61

Note: Assumes average 0.67 m/s^2 acceleration and 1.2 m/s^2 deceleration rate (12-m standard diesel bus). Use the zero dwell time column for express buses slowing, but not stopping at stations (40 km/h station speed limit and 100-m-long speed zone through station assumed). Assumes passing lane available for non-stopping buses and no at-grade pedestrian crossings within the station.

Exhibit 6-73m
Estimated Base Bus Running Time Losses, t_l (min/km)

Condition	Bus Lane	Bus Lane, No Right Turns	Bus Lane With Right Turn Delays	Bus Lanes Blocked by Traffic	Mixed Traffic Flow
CENTRAL BUSINESS DISTRICT					
Typical		0.7	1.2	1.5-1.8	1.8
Signals Set for Buses		0.4	0.8		
Signals More Frequent Than Bus Stops		0.9–1.2	1.5–1.8	1.8–2.1	2.1–2.4
ARTERIAL ROADWAYS OUTSIDE THE CBD					
Typical	0.4				0.6
Range	0.3–0.6				0.4–0.9

Source: Derived from *TCRP Report 26* (*21*).
Note: Traffic delays reflect peak conditions.

APPENDIX B: DWELL TIME DATA COLLECTION

INTRODUCTION

As discussed in Section 2, passenger service times (and dwell times) can vary greatly depending on many factors. For example, the average passenger boarding times shown in Exhibit 6-4 for level boarding ranged from 1.6 to 8.4 s. For this reason, it is recommended that field data be collected when estimating passenger service times and dwell times for a given system.

Although a transit vehicle's passenger service time may be affected by many factors, most of these factors are constant for a given system. For this reason, the principal determinants of service time typically include aspects of passenger demand. Therefore, for a given transit system with constant operating characteristics (i.e., fare collection system, number and width of doors, number of steps to board/alight, etc.), the major factors affecting service time will be

- The number of passengers boarding,
- The number of passengers alighting, and
- The number of passengers on board.

This appendix presents methodologies for measuring passenger service times and dwell times in the field for buses and light rail transit (LRT).

PASSENGER SERVICE TIMES

Passenger movements at most stops are small, typically one or two passengers boarding or alighting per stop. In these situations, dwells are relatively independent of passenger service times and it is not possible to collect statistically useful data. To determine passenger service times for use in evaluating the differences between systems (such as single- and dual-stream doors, high- and low-floor buses, or alternate fare collection systems), data collection should be done only at high-volume stops. These stops are typically downtown or at major transfer points. The data collection effort will require one or two persons, depending on the number of passengers.

The following are steps that may be used to collect field data on passenger service times. An example of a data collection sheet is shown in Exhibit 6-B1.

1. From a position at the transit stop under study, record the identification number and run number for each arriving vehicle.
2. Record the time that the vehicle comes to a complete stop.
3. Record the time that the doors have fully opened.
4. Count and record the number of passengers alighting and the number of passengers boarding.
5. Record the time that the major passenger flows end. (Note: This is somewhat subjective but essential to correlate flows per unit of time. The time for stragglers to board or exit should not be included.)
6. When passenger flows stop, count the number of passengers remaining on board. (Note: If the seating capacity of the transit vehicle is known, the

number of passengers on board may be estimated by counting the number of vacant seats or the number of standees).

7. Record the time when the doors have fully closed.
8. Record the time when the vehicle starts to move. (Note: Leave time should exclude waits at timepoints or at signalized intersections where the vehicle must wait for a traffic signal to turn green.)
9. Note any special circumstances. In particular, any wheelchair movement times should be noted.

The passenger service time for each transit vehicle arrival is computed by taking the difference between the time that the door opens and the time that the main flow stops. The service time per passenger is computed by dividing the number of passengers boarding (or alighting) by the total service time.

Exhibit 6-B1
Sample Passenger Service Time Data Collection Sheet

Passenger Service Time Data Sheet #____

Date _____________ Time ___________

Route ________ Location ______________________ Direction ___________

Bus Run #	Arrival Time	Doors Open	Main Flow Stops	Doors Close	Bus Leaves	Passengers Boarding		Passengers Alighting		Passengers Departing On Board	Notes
						Front	Rear	Front	Rear		

DWELL TIMES

The procedure for determining dwell times is similar to that for estimating passenger service times, except that dwell times are best determined with ride checks. With ride checks, the observer rides the transit vehicle over the entire route for several runs at different times of day. A single observer can usually monitor both doorways on a 40-ft (12-m) bus. While it is more difficult for a single observer to handle articulated buses that have three doorways, it is possible with an experienced checker. For LRT vehicles, at least one observer per car will be required. Automated equipment can also monitor dwell times, possibly in conjunction with automatic passenger counting equipment.

Usually a given route will have similar equipment. Where equipment types such as single or double doors, rigid or articulated bodies, or high- or low-floor cars are intermixed, separate data sets should be obtained for each type of equipment. A sample data collection sheet is shown in Exhibit 6-B2. This sheet can be adapted to also record traffic and intersection delays. Where passenger service times are not needed, the doors open, end of passenger flow, doors close columns can be omitted. The following are steps that may be used to collect field data for estimating dwell times:

1. From a position on the transit vehicle, record the stop number or name at each stop.
2. Record the time that the vehicle comes to a complete stop.
3. Record the time that the doors have fully opened.
4. Count and record the number of passengers alighting and the number of passengers boarding.
5. Record the time that the major passenger flows end.
6. When passenger flows stop, count the number of passengers remaining on board. (Note: If the seating capacity of the transit vehicle is known, the number of passengers on board may be estimated by counting the number of vacant seats or the number of standees).
7. Record the time when doors have fully closed.
8. Record the time when the vehicle starts to move. (Note: Waits at timepoints or at signalized intersections where the dwell is extended due to a red traffic signal should be noted but *not* included in the dwell time. A delay due to a driver responding to a passenger information request is an everyday event and *should* be included in the dwell time calculation. Time lost dealing with fare disputes, lost property, or other events should *not* be included.)
9. Note any special circumstances. In particular, any wheelchair movement times should be noted. Whether this is included in the mean dwell time depends on the system. Dwell times due to infrequent wheelchair movements are often not built into the schedule but rely on the recovery time allowance at the end of each run.

The observer must use judgment in certain cases. At near-side stops before signalized intersections, the driver may wait with doors open as a courtesy to any late-arriving passengers. The doors will be closed prior to a green light. This additional waiting time should *not* be counted as dwell time but as intersection delay time.

Exhibit 6-B2
Sample Dwell Time Data Collection Sheet

Dwell Time Data Sheet #____

Date ________ Time _______ Bus No. _____ Bus Type________

Route _______ Run No. _____ Direction ________

Stop # and Name	Arrival Time	Doors Open	Main Flow Stops	Doors Closed	Bus Leaves	Passengers Boarding		Passengers Alighting		Passengers Departing On Board	Notes
						Front	Rear	Front	Rear		

APPENDIX C: BUS BUNCHING AND PERSON CAPACITY

Transit services are typically designed with sufficient buses to ensure that an agency's maximum schedule load is not exceeded. Agency policies differ on whether this maximum load applies to every bus or to the average load of all buses on a route during a specified time period (e.g., one-half hour), but in any event, no pass-ups should occur.

Predictable surges in demand may be accommodated by adjusting headways or adding an extra bus. Tweaking the schedule is less effective for handling random surges.

If passengers arrived evenly throughout the course of an hour, the number of buses per hour required to serve those passengers would be simply the hourly passenger demand divided by the maximum schedule load per bus. More typically, more passengers will arrive for some buses than for others, due to the normal randomness of passengers' travel from day to day and from predictable surges at certain times (e.g., from a school letting out). If passenger demand requires frequent service and if buses are scheduled as though passengers arrive at an even rate, the result will be that some buses will experience overcrowding. The number of buses per hour required to accommodate typical peak 15-min loads can be determined as follows:

Equation 6-40

$$f_{min} = \frac{P_h}{P_{max}(PHF)}$$

where

f_{min} = minimum frequency to accommodate peak 15-min passenger demands without overcrowding (bus/h),

P_h = hourly passenger volume (p/h),

P_{max} = maximum schedule load per bus (p/bus), and

PHF = peak-hour factor.

For example, if 600 passengers must be served during the peak hour and if the maximum schedule load is 60 passengers per bus, 10 buses per hour would be needed if passengers arrived at an even rate (i.e., PHF=1.00). If the peak15-min passenger demand were 20% higher than the average demand over the peak hour (i.e., PHF=0.83), the number of buses required to avoid overcrowding would be 12. Adjusting scheduled headways to respond to regular peaks in demand is another option that can reduce the number of extra buses required to avoid overcrowding (*C-1*).

In practice, the extra passengers would cause dwell times to be longer than normal, the first bus will fall further and further behind schedule, and the following bus will tend to run early.

The PHF concept can be extended to address crowding issues on routes experiencing a moderate amount of bunching. If, as a simplified example, buses are scheduled to arrive every 10 min, passengers arrive at an even rate, and one bus operates 5 min late, that bus will pick up all of its normal passengers at a stop, plus half of the passengers that would normally take the following bus. The late bus will experience overcrowding, carrying more passengers than the schedule assumes, while the following bus will pick up half of its normal load, and some of its offered capacity will go unused.

As an extreme example, imagine that buses are scheduled to arrive every 5 min but that actually two arrive in close succession every 10 min. The effective frequency of the route in this case is 10 min, as that is the average interval between bus arrivals. The effective frequency can be determined from the following:

$$f_{eff} = \frac{f}{1 + c_{vh}}$$

Equation 6-41

where

f_{eff} = effective frequency (bus/h),

f = scheduled frequency (bus/h), and

c_{vh} = coefficient of variation of headways (standard deviation of headways divided by the mean headway).

The coefficient of variation of headways should be calculated using the population standard deviation; this produces a c_{vh} of 1.0 when two buses always arrive together and a c_{vh} of 0.5 when buses are consistently one-half headway off-headway, as in the previous examples.

The average loading of late buses during the peak 15 min can be calculated as shown in Equation 6-42. Dividing the average hourly passenger demand by the peak-hour factor gives the average peak 15-min load; dividing the result by the effective frequency gives the average load per late bus during the peak 15 min.

$$P_l = \frac{P_h}{(PHF)f_{eff}}$$

Equation 6-42

where P_l is the average load per late bus during the peak 15 min (p/bus) and other variables are as defined previously.

Research is required to develop procedures to estimate the effects of various factors (e.g., traffic, transit priority, bus operator experience) on headway adherence. Adding additional buses to address overcrowding may not have an effect on the most crowded buses, if the added buses end up bunched as well. Since the added buses entail added operating costs for an agency, other measures to improve reliability, such as those discussed in Section 7, could prove to be more cost effective for relieving overcrowding.

REFERENCE

C-1. Boyle, D., J. Pappas, P. Boyle, B. Nelson, D. Sharfarz, and H. Benn. *TCRP Report 135: Controlling System Costs: Basic and Advanced Scheduling Manuals and Contemporary Issues in Transit Scheduling.* Transportation Research Board of the National Academies, Washington, D.C., 2009. http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_135.pdf